Sniper Localization using a Helmet Array

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ABSTRACT

The presence of snipers in modern conflicts leads to high insecurity for the soldiers. In order to improve the soldier's protection against this threat, the French German Institute of Saint-Louis (ISL) and Rheinmetall Defence Electronics GmbH (RDE) work together to develop a helmet integrated acoustic array for the detection and localization of snipers .This paper summarizes the results obtained during the collaboration between RDE and the ISL concerning the detection and the localization of the Mach and muzzle waves generated by rifle shots. It summarizes the technical choices that have been made and explains the algorithms that have been presented in Meppen in November 2005. We built three prototypes which showed good performances. The measurements have been made in realistic conditions: helicopters and aircrafts flying near the arrays (sometimes, the distance microphones/vehicle was smaller than 100 meters), armoured vehicles passing near the arrays, 155mm calibre shots, etc…

The estimation of the distance between the shooter and the arrays is made with two different techniques. The first one is usable when several arrays have detected the shot, and the second technique uses the information gathered by one head equipment alone. The results obtained with those two techniques will be discussed in the paper.More than 2000 shots have been detected and localized successfully in real-time. No false alarms have been observed.

Keywords: Sniper detection, localization, high SPL microphones, helmet-array

1.0 INTRODUCTION

The presence of snipers in modern conflicts leads to high insecurity for the soldiers. In order to improve the soldier's protection against this threat, the French German Institute of Saint-Louis (ISL) and Rheinmetall Defense Electronics GmbH (RDE) started to work together in order to develop an acoustic array for the detection and localization of snipers. In November 2005 three demonstrators of a detection system, working in real-time and using acoustic arrays mounted on helmets, were presented. 2000 shots have been fired with calibres between 5.56 and 12.7 mm at distances between 100 and 450 meters. The algorithms developed by the ISL showed good performances concerning the detection and localization of the shooter. These first prototypes were able to detect and give an estimation of the direction of arrival of the shot. Some more possibilities are studied in order to allow the estimation of the calibre and the distance separating the shooter and the arrays.

Hengy, S. (2006) Sniper Localization using a Helmet Array. In *Battlefield Acoustic Sensing for ISR Applications* (pp. 7-1 – 7-16). Meeting Proceedings RTO-MP-SET-107, Paper 7. Neuilly-sur-Seine, France: RTO. Available from: http://www.rto.nato.int/abstracts.asp.

First, the summary of the results obtained during the experiments at the WTD-91 in November 2005 will be presented. The detection algorithm is presented in the second part of this paper. Then, the estimation of the distance between the sniper and the arrays is discussed. Two algorithms have been written. They are presented in the third part of this report.

2.0 DETECTION OF A SMALL CALIBRE SHOT

Two waves are generated when a rifle shot is triggered: the Mach wave and the muzzle wave. The Mach wave is generated by a supersonic bullet (Figure 1), and the muzzle wave is generated by the explosion of the powder in the barrel (Figure 2). The Mach wave has a characteristic N-shape. The spectral analysis of this wave allows its detection and accurate classification when the sampling rate is high (>80kHz).

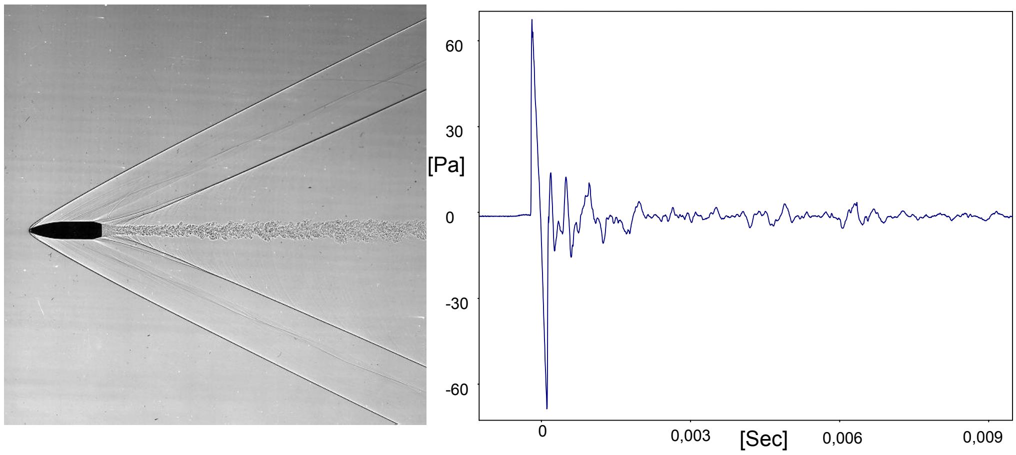

Figure 1: Shock wave generated by the bullet and its acoustic signature

The muzzle wave has got more energy in the lower frequency range than the Mach wave.

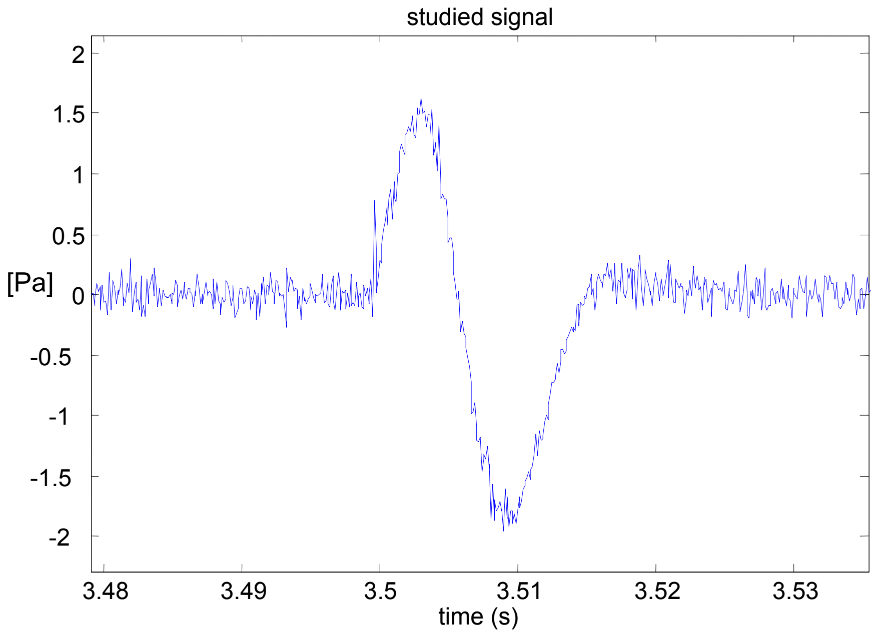

Figure 2: reference signal (muzzle wave)

The detection algorithm uses classical signal processing techniques (inspired from Speech processing techniques like speech blank detection). It has been developed so that no false alarm occurs when continuous noise sources stay or move near the arrays. This algorithm has been tested in simple cases:

- one sniper, one shot
- one sniper, several shots, time interval between two shots >3 seconds
- one sniper, shot volley, time interval between two shot volleys >3 seconds

It has shown good performances in every case. We summarize this detection algorithm in the next paragraph.

The detection scheme is visible on figure 3. The signal received by the microphones is saved in a 5 ms buffer. This buffer is used in order to compute the energy of the signal (on all the frequency range) and is compared to the mean value of the energy, computed with a 1 second signal block.

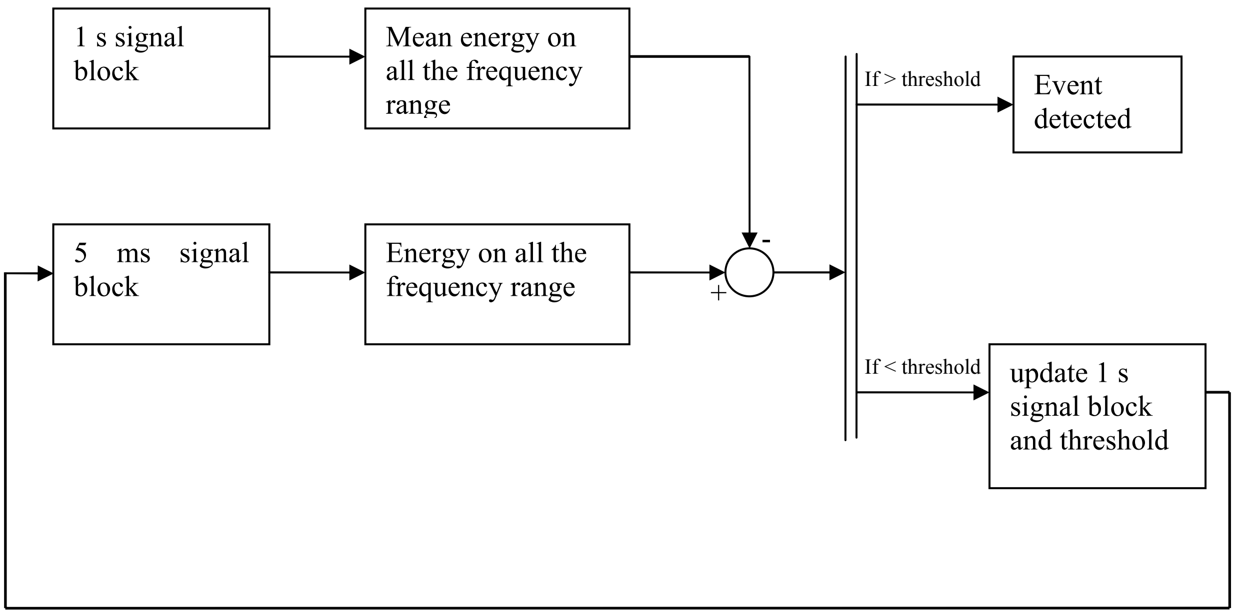

Figure 3: detection scheme

A threshold is defined in order to determine the cases in which an impulse event has been detected. The threshold is defined regarding the standard deviation of the values of the energy on the one second signal block and is updated each time a new 5ms block is studied.

This technique is also efficient if a continuous noise source is present near the arrays (for example a vehicle which engine is running).

Then the classification of the detected event is made. Depending on the sampling rate, there are two different ways that are used in order to make this classification. If the sampling rate is low (10 kHz), we calculate the bandwidth and the low and high cut-off frequencies of the detected wave. Those values are compared to the theoretic values of an N-wave which would have the same characteristics as the detected signal (peak level, period). This technique is unfortunately not reliable if additional noise is also measured (e.g. car engine near the array). The estimation of the bandwidth and the low cut-off frequency is not good in that case, thus, the efficiency of the classification is lowered and some false alarms are possible.

If the sampling rate is high (>80kHz), some other characteristics of the N-shaped wave can be used ([5],[6],[7],[8]). The accuracy of the classification, like the one of the measurement of the characteristics of the signal, is increased. The acquisition of the signal is made so that one channel is sampled at a frequency of 80kHz while the others are sampled at a frequency equal to 10 kHz.

If the detected wave is not classified as a Mach wave, the algorithm localizes the Direction of Arrival (DOA) of the event and its position only if there are several arrays that have detected the same event.

If the detected wave is classified as a Mach wave, the algorithm tries to detect a second wave, which would be the muzzle wave. In order to detect this second wave, the same technique is used. Five ms blocks are studied. Their energy is computed in the frequency range 50-500Hz. This operation is carried out during 2.5 seconds following the Mach wave detection; this corresponds to the maximum difference in Time of Arrival (ToA) between the Mach and the muzzle wave for a 14.5mm calibre rifle at a distance of 1200 meters.

The algorithm searches for the maximum of energy in these 2.5 seconds of buffered signal, and if the energy is sufficient (a threshold is defined), the algorithm considers that a muzzle blast has been detected.

The algorithms have been tested on simulated and real data. Those results have been presented in [8]and [9]. It showed that the algorithm is efficient as long as the signal to noise ratio is strong enough. If a continuous noise is generated near the acoustic array, the detection is more difficult, and some more techniques should be used in order to minimize the undesired signals (e.g. the sounds generated by the engine of near vehicles).

Except for this particular case, the detection results have been satisfying for isolated small calibre shots in simulations and real data, even with a weapon (G22) equipped with a silencer at large distances (600 meters).

The prototypes that have been presented in Meppen in November 2005 used this detection algorithm. The localization algorithms that have been used are typical array signal processing techniques: beamforming (for the muzzle wave) and Time of Arrival (ToA) estimation (for the Mach wave). The estimation of the ToA and the DOA of the two waves leads to the estimation of the distance between the shooter and the arrays.

3.0 DISTANCE ESTIMATION

3.1 Propagation characteristics of the waves

The times of arrival of the two sound waves of interest (muzzle and Mach wave) are computed as follows:

$$t_{muz} = t_0 + t_{SH} = t_0 + \frac{\|SH\|}{c} \quad \text{3-1}$$

$$t_{Mach} = t_0 + t_{SD} + t_{DH} = t_0 + \int_S^D \frac{1}{V} ds + \frac{d_{miss}}{c.\cos(\alpha)} \quad \text{3-2}$$

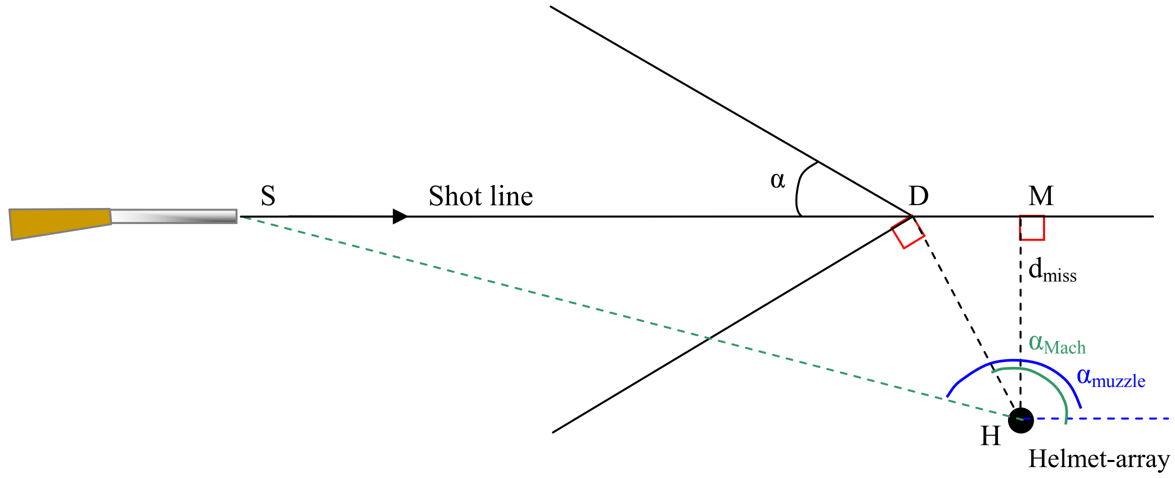

Figure 4: geometric characteristics of the Mach wave and the muzzle wave.

According to Whitham's theory, the characteristic N-shape of the Mach wave contains some more information. The amplitude p_{MAX} and duration Δt of a shock wave produced by small calibre projectiles are expressed as:

$$\frac{p_{MAX}}{P_0} = 0.53 \cdot \frac{(M^2-1)^{\frac{1}{8}}}{(d_{miss})^{\frac{3}{4}}} \cdot \frac{d_p}{l_p^{\frac{1}{4}}} \quad \textbf{3-3}$$

$$\Delta t = \frac{1.82}{c} \cdot \frac{M \cdot (d_{miss})^{\frac{1}{4}}}{(M^2-1)^{\frac{3}{8}}} \cdot \frac{d_p}{l_p^{\frac{1}{4}}} \quad \textbf{3-4}$$

d_p and l_p are the diameter and the length of the projectile, d_{miss} is the miss distance, and P_0 is the ambient pressure. We assume that for almost all bullets, the length can be derived from the calibre following this equation:

$$l_p = C_1 \cdot d_p \quad with \quad C_1 \simeq 4$$

These expressions lead to:

$$d_p = 0.45 \cdot C_1^{\frac{1}{3}} \cdot \left(\frac{c \cdot \Delta t}{M}\right)^{\frac{4}{3}} \cdot \frac{(M^2-1)^{\frac{1}{2}}}{(d_{miss})^{\frac{1}{3}}} \quad \textbf{3-5}$$

3.2 "Stand alone" solution

In November 2005, it was necessary to have a communication network between the arrays and a central computer. The central computer gathers the information of all arrays and does a fusion of this data in order to estimate the position of the shooter. It delays the time of arrival of the information for the soldier who uses this system (the position information is sent to the soldier only once all the soldiers in the group detected the shot).

At the ISL, an algorithm has been developed that allows an estimation of the position (azimuth and distance) of the sniper with one single helmet-array. According to equation 3-5, in order to estimate the calibre of the bullet, we need to know the speed of the bullet (M), the miss distance (d_{miss}) and the length of the N-wave (Δt).

3.2.1 Estimation of Δt:

There are two ways to do the estimation of Δt:

- The time signal can be used to estimate Δt. This technique uses two thresholds defined by the user. Its accuracy depends on the sampling rate. Some difficult cases appear if a reflection is present on the time signal.
- The spectral analysis of the signal allows the estimation of Δt. This is only possible if a measurement with a large bandwidth is available (the minimum sampling rate that is acceptable is equal to 80kHz). This technique is better than the analysis of the time signal. It is easy to eliminate reflections if some are present, and the estimation of Δt is more accurate.

3.2.2 Estimation of V and d_{miss}

First, the time of arrival (t_{Mach} and t_{muz}) and the Direction Of Arrival (DOA) of the Mach wave and the muzzle wave are estimated. Then, the value of p_{MAX} is measured for the detected Mach wave.

We assume that the velocity of the projectile varies between 400 and 1000 meters per second. For each velocity of the projectile varying between those two values, the characteristics of the N-wave allow the estimation of the miss distance and the Mach cone aperture (α).

$$M = \frac{V}{c} \qquad \textbf{3-6}$$

$$\alpha = arc\sin\left(\frac{1}{M}\right) \qquad \textbf{3-7}$$

$$d_{miss} = \Delta t \cdot \frac{c^2}{V} \cdot \frac{P_0 \cdot \sqrt{M^2 - 1}}{3.44 \cdot p_{MAX}} \qquad \textbf{3-8}$$

$$d_p = \left(\frac{p_{MAX}}{P_0}\right)^{\frac{4}{3}} \cdot \frac{d_{miss}}{\left(2.635 \cdot e^{-4}\right) \cdot \left(M^2 - 1\right)^{\frac{1}{6}}} \qquad \textbf{3-9}$$

Knowing d_{miss}, the DOA of the muzzle wave and the DOA of the Mach wave, it is easy to calculate the distances DH and DS (figure 4).

Then, a comparison is made between the actual value of $\Delta T = t_{muz} - t_{Mach}$ and the value determined thanks to the preceding calculations. The quadratic error is calculated (3-10).

$$\varepsilon = \left| \Delta T - \left(\frac{SH}{c} - \left(\frac{SD}{V} + \frac{d_{miss}}{c \cdot \cos(\alpha)} \right) \right) \right|^2 \qquad \textbf{3-10}$$

In order to select the good values for $\boldsymbol{d_{miss}}$ and $\boldsymbol{V}$, the quadratic error is calculated for each value of the velocity of the projectile between 400 and 1000m/s. The minimum value of the error gives estimates of the miss distance, the calibre, the velocity of the bullet and the distance shooter/array.

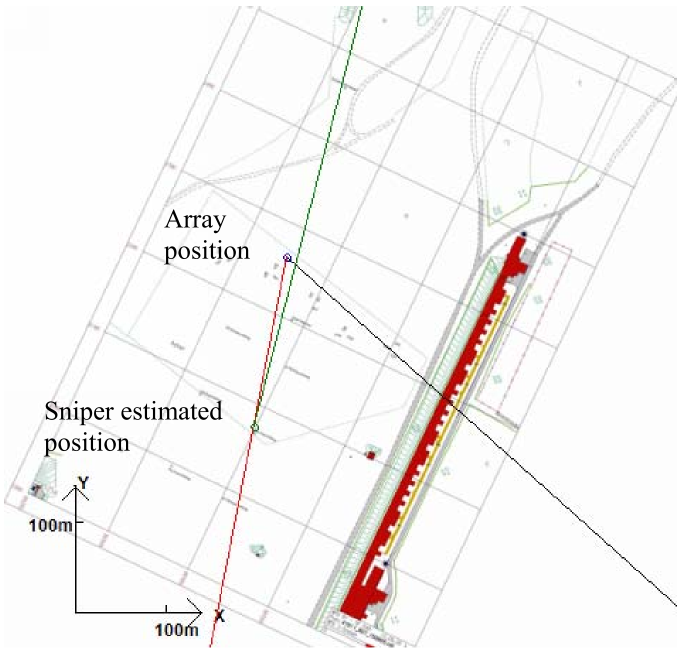

Figure 5: Results obtained for a shooter at 200 meters from the helmet array: results for helmet A

On figure 5, the red line, the black line and the green line represent respectively the estimated values of the DOA of the muzzle wave, the DOA of the Mach wave, and the bullet trajectory. The position of the sniper is the starting point of the green line. In this case, the estimation of the position of the shooter is correct.

The measurements of the length of the N-wave and of the maximum acoustic pressure are the most important parts of the distance estimation. Their influence is very important on the estimation of the distance between the shooter and the array.

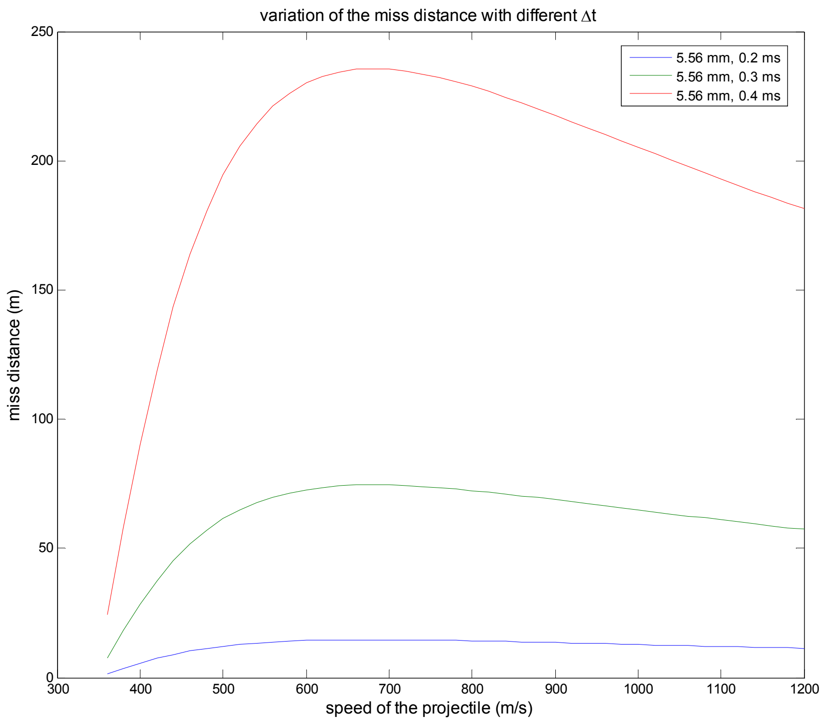

Figure 6:Variation of the miss distance for calibre 5.56mm at different values of Δt

Figure 6 shows the importance of a good estimation of the length of the N-wave. An estimation error equal to 0.1 ms induces a variation of the estimation of the miss distance over 50 meters at a projectile speed equal to 700 m/s.

With a sampling rate equal to 10 kHz (0.1 ms between two samples), the measurement of the N length will not be good enough to get a precise estimation of the miss distance and the position of the shooter. The higher the sampling rate is, the better this estimation will be.

The problems induced by the low sampling rate are shown on figure 7. The estimation of the distance is correct for helmet A, but is not good for helmet B. This is due to the estimation of the N-length which is not good for helmet B (estimation of miss distance and calibre are too approximate to get good results for the distance shooter/array). We can also see that the estimation of the miss distance for helmet C is not correct (the trajectory of the bullet actually passes between helmet A and B).

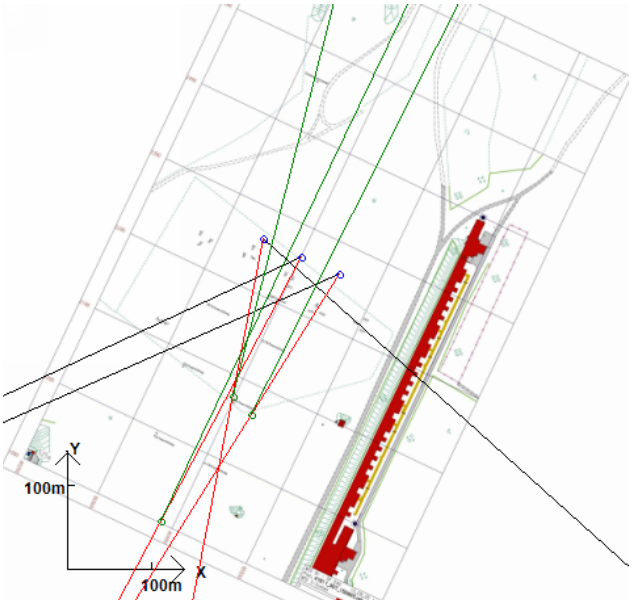

Figure 7: Results obtained for a shooter at 200 meters from the helmet array: results for helmet A,B and C.

The necessary 80 kHz sampling rate for an efficient classification of the Mach wave presented in 2.0 allows a precise estimation of Δt, and thus, a better estimation of the distance shooter/array.

A second solution in order improve the estimation of the distance shooter/array, is the use of a network of arrays. This solution is presented in the next section. It uses the data sent to a central computer by each array. This computer, once the data is gathered, makes an estimation of the trajectory of the bullet and the distance shooter/array.

3.3 Use of a network of arrays

If a number of arrays are on a survey area, it is possible to use them together for the estimation of the speed, the calibre and the trajectory of the bullet, and also the distance between the shooter and the group of arrays.

When a Mach wave is detected, each array sends the following data:

- Time of Events (for example GPS time to get a synchronized clock between each array): Mach wave and muzzle wave
- Direction of Arrival of the Mach wave and the muzzle wave.
- Position of the array (GPS measurement)

The scheme followed by the algorithm in order to estimate the position of the shooter is shown on figure 8. First, the estimation of the DOA of the Mach wave for each helmet is used in order to get an estimation of the bullet speed and the shot line (in green on figure 9). This is possible by reconstruction of the Mach cone: for a good estimation of the speed of the bullet, it is necessary to have antennas on both sides of the trajectory.

3.3.1 Arrays on both sides of the bullet trajectory

The DOA of the Mach wave is used in order to determine which arrays are at the left and at the right of the trajectory (equation 3-7). This helps for the estimation of the speed of the projectile and the angle of the trajectory of the bullet. Then, this information is combined with the time of arrival of the Mach wave and is used to estimate the miss distance (black dashed line on figure 9), e.g. the distance between each array and the trajectory of the bullet.

Then the estimation of the calibre is possible, and finally, using the time of arrival of the muzzle wave, it is possible to estimate the position of the shooter (red square on figure 9). Once again, a quadratic error is calculated, in order to compare the theoretic behaviour of a bullet (with the estimated calibre and projectile speed), and the actual measurements. The minimum value of the quadratic error gives the estimate of the sniper position.

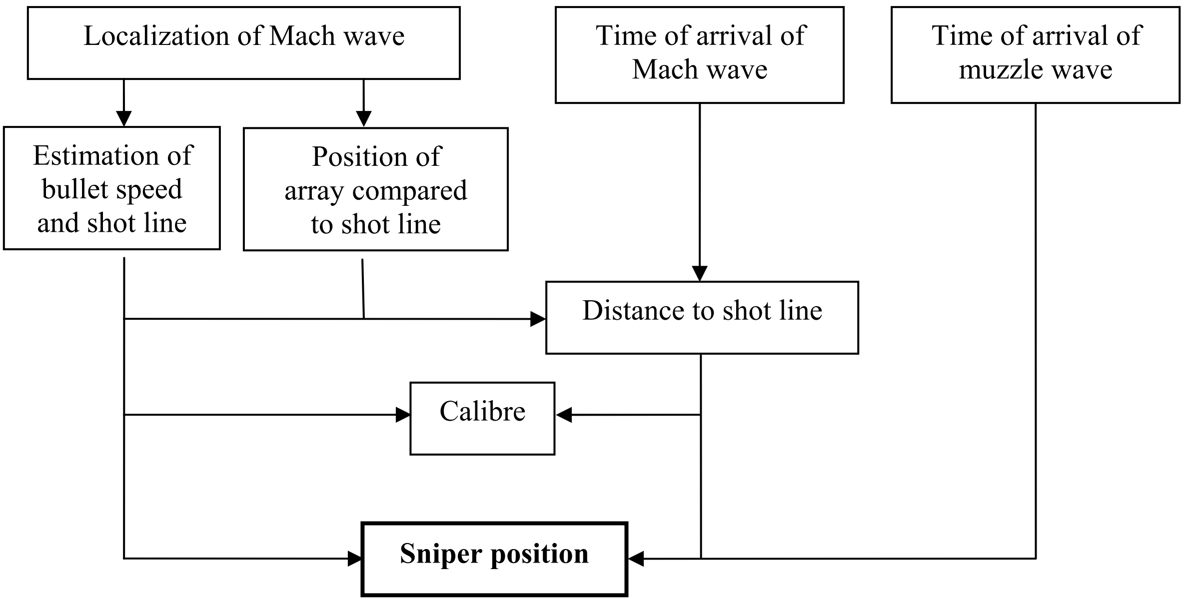

Figure 8: algorithm scheme to estimate the sniper position

We emphasized in [9] that the accuracy of this technique depends on the quality of the estimation of the DOA of the Mach wave. As the acoustic shadow induced by the presence of the helmet is not taken into account with the tested prototypes, some errors occur while estimating the DOA of the Mach wave. Thus, the estimation of the position of the shooter with the prototypes was not precise.

Measurements made in the anechoic room in the ISL showed that the impulse response of the helmet array is, for frequencies lower than 6 kHz, equivalent to a time delay induced by the geometry of the helmet and the sound velocity. A three dimensional model of the helmet has been made and will be implemented in the next versions of the localization algorithm.

When, like on figure 9, the used arrays were ISL arrays (for which the impulse response has been determined in [2]), the estimation error was smaller than 10% of the actual sniper/array distance, which matches once again the NATO requirements for acoustic warning systems.

This first algorithm is only usable if the helmets constituting the network are on both sides of the bullet trajectory. In the next section, we present the algorithm that should be used when the helmets are all on the same side of the trajectory.

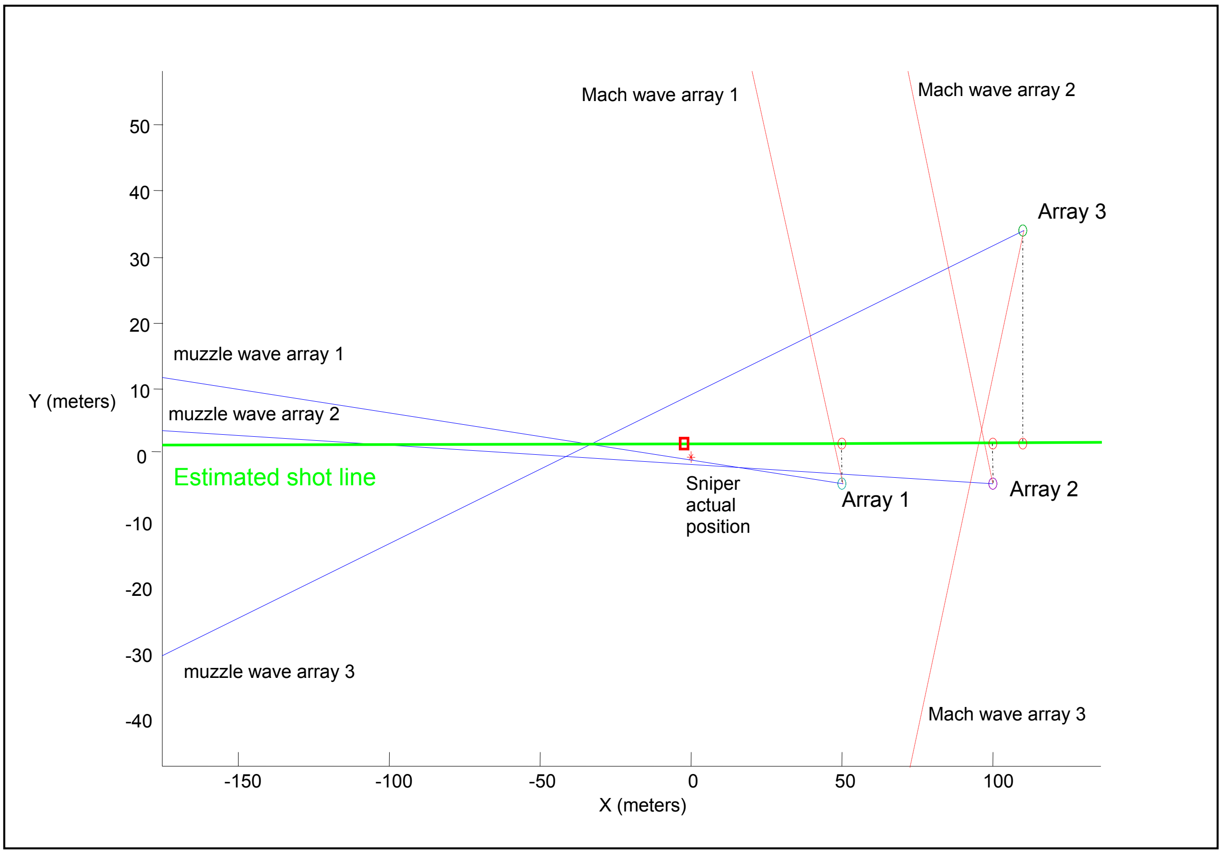

Figure 9: Estimation of the position of the sniper

3.3.2 Arrays on one side of the bullet trajectory

If the helmets are all on the same side of the trajectory, the used algorithm should follow the same scheme as the "stand alone" solution: make the speed of the projectile vary from 400 to 1000 m/s, and compute the quadratic error (equation 3-11). But instead of applying the algorithm on a single helmet, it is applied simultaneously on all the helmets present on the zone, leading to a more accurate estimation of the position of the shooter.

The minimum of the quadratic error gives the estimates of the projectile velocity, of the calibre and of the shooter/array distance.

$$\varepsilon = \sum_{i=0}^{N_{ant}} \left| \Delta T_i - \left(\frac{SH_i}{c} - \left(\frac{SD_i}{V_i} + \frac{[d_{miss}]_i}{c \cdot \cos(\alpha)} \right) \right) \right|^2 \quad \text{3-11}$$

The more helmets are present on the survey area, the better the results for the estimation of the trajectory and the distance shooter/arrays will be.

4.0 MEPPEN: NOVEMBER 2005

4.1 Summary of the results of the experiment

The main characteristics of the experiment were as follows:

- three helmets
- calibre 5.56 (weapon : G36) and 7.62 mm (weapon : G3):
- October 2005 : more than 135 shots on 3 helmets => more than 405 shots to evaluate
- November 2005 : more than 560 shots registered on 3 helmets => more than 1700 shots to evaluate
- 3 shots with calibre 12.7mm (weapon : G82) in November 2005
- 9 shot positions (from 100 to 450 meters between shooter and arrays)
- Average temperature ~15 °C

The arrays were above grass: the distance between the arrays and the first obstacles was more than 200 meters; there were no objects which could generate reflections close to the arrays (the reflections due to the forest are recorded 0.5 seconds after the direct wave arrival). Figure 10 shows one prototype as it has been set up on the proving ground.

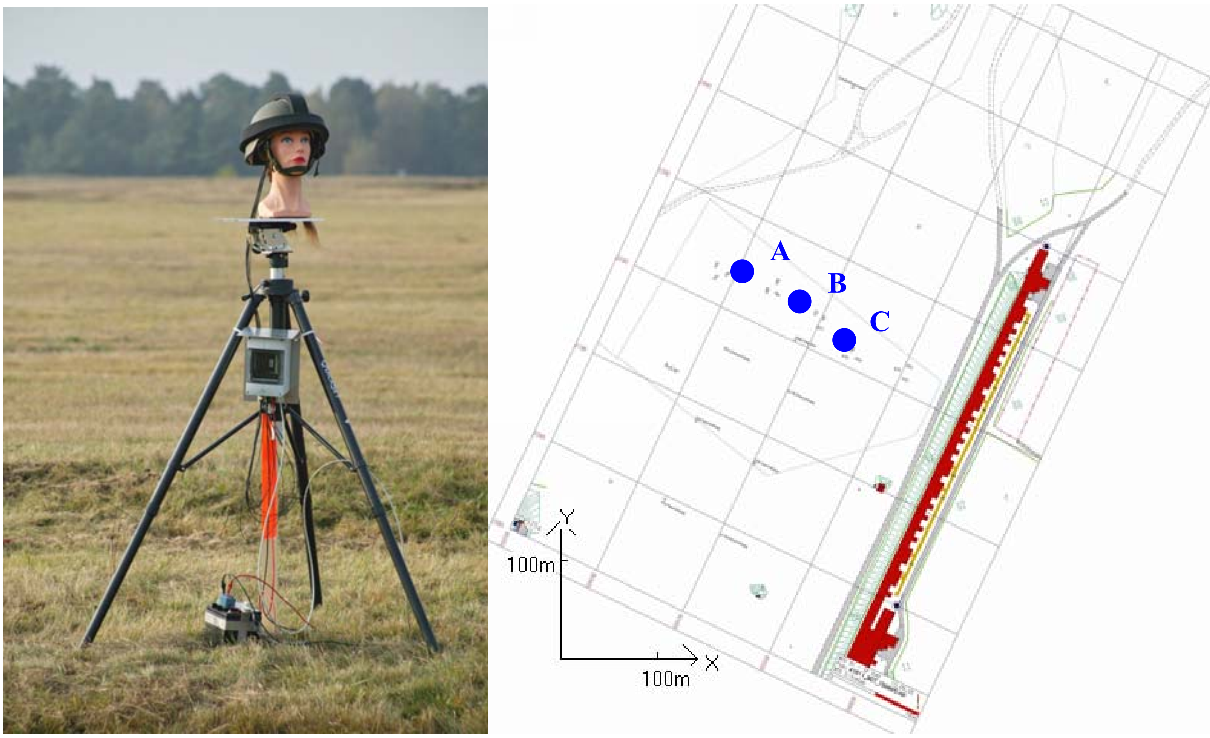

Figure 10: view of one array and of the position of the three arrays.

Three prototypes were deployed on the test field in Meppen (Figure 1). Their positions have been determined with a differential GPS. The helmets were heading to the North. The exact orientation has been measured using acoustical techniques.

The algorithms presented by ISL and RDE allowed the detection and localization of the two waves generated by small calibre shots (Mach and muzzle wave). Once the detection and localization have been made, a triangulation with the results of the muzzle wave is made in order to estimate the position of the shooter.

4.1 Results

Table 1 shows the global results obtained with the three prototypes presented in November. The detection algorithm has not been triggered by any "non-weapon" noise. Even if aircrafts, tanks and helicopters came close to the arrays (sometimes at distances smaller than 100 meters), no false alarm has been observed,. This is due to the efficient Mach wave classification algorithm, based on spectrum analysis of the detected signal.

	Helmet A	Helmet B	Helmet C	Network result
Number of shots	> 695	> 695	> 695	>2100
False alarms	**0**	**0**	**0**	**0**
Undetected shots	**0**	**0**	**1**	**0**
Undetected or badly detected muzzle Wave	**2**	**2**	**0**	**3**

Table 1: global results for the detection

False alarm: detection of a "non-weapon" noise

Undetected shot: a shot occurred, but no detection made.

Undetected or badly detected muzzle wave: the selection of the actual muzzle wave has not been correct.

On helmet A and B, one of the bad detections of the muzzle wave has been observed because of an artillery shot that occurred in the 2.5 second "survey window" after the Mach wave detection (figure 11). The algorithm has not been designed to detect more than 1 event during this "survey window", thus, if an artillery shot (or another distant small calibre shot) occurs, and its energy in the low frequencies (50-500 Hz) is greater than this of the actual muzzle wave, this event will be selected.This explains the errors that have been observed for helmet A and B and displays one weakness of the algorithm.

If more than one low frequency event is detected, the algorithm should localize all the low frequency events. It should also start to search for a second Mach wave that could have appeared in the "survey window". If an algorithm is developed and is able to do that, its efficiency if several shooters are present will increase. The major difficulty will be to detect actual Mach wave, and not only reflections of the first detected Mach wave.

The results of the localization algorithms are good. They match the NATO requirements for acoustic warning systems (accuracy should be better than +/- 10 degrees for NATO) [9].

In Meppen, the localization algorithms used the triangulation for the estimation of the position of the sniper. This technique implies the presence of a network of arrays. This means that the arrays should communicate, which is a shortcoming for the discretion of a military operation. More, triangulation gives only satisfying results if the sniper is not at a far distance from the arrays. The accuracy of the estimation of the distance rapidly decreases if the shooter is far from the group of arrays.

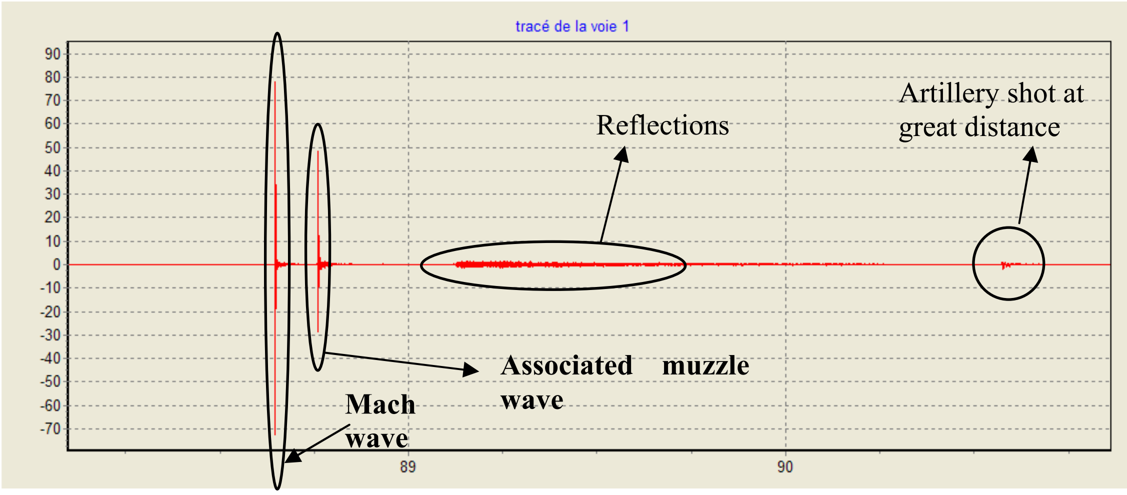

Figure 11: Bad detection for muzzle wave

Two new techniques have been presented in the preceding section that enhance the quality of the estimation of the distance shooter/array: the first one needs a network of arrays and uses the characteristics of the Mach wave to estimate the distance between the shooter and the arrays, the miss distance, the calibre and the speed of the projectile. The second method uses one single array.

The undetected shot on helmet C is due to the presence of a vehicle near this array, which led to the low signal to noise ratio that has been observed for that measurement. This shows that, at the moment, the algorithm is not able to warn the user if the environmental noise is too strong.

There are two solutions for this problem: the first one would be the use of a noise reduction process. This technique has a high computational cost and will be difficult to use in real time if being added to the detection and localization processes. The second solution is to decrease the detection threshold value. In that case, every low intensity impulse noise could be detected. If it is possible to use a sampling rate equal to 80 kHz, it will be possible to separate high frequency noises and real Mach waves, which permits to lower the threshold and increase the efficiency of the detection in noisy environments.

5.0 CONCLUSION

Three helmet-array prototypes have been presented in November 2005 in Meppen. A detection and localization algorithm developed in the ISL, joint to the hardware developed by RDE equipped those prototypes. The detection and localization algorithms that were used showed good performances in simple cases:

- one sniper, one shot,
- one sniper, several shots, time interval between two shots >3 seconds,
- one sniper, shot volley, time interval between two shot volleys >3 seconds.

The presence of continuous sound sources near the prototypes does not disturb the detection of sniper shots if the sampling rate of the system is greater than 80 kHz. Indeed, the classification of the Mach wave is excellent when the sampling rate is that high, thus, the detection of the aggressive shot is not a problem.

Two techniques for the estimation of the distance between the shooter and the arrays have been presented in this paper. The one uses a single array and its efficiency depends on the sampling rate that is used, the other uses a network of arrays and needs a communication between the arrays.

The second technique has already shown good performances (also for a shooter at 600 meters from the arrays) with three helmets-arrays for which the helmet "shadow" was included in the algorithms.

The first technique has been tested on low sampling rate signals (10kHz), showing a large variance between two estimations. This is due to the poor quality of the N length and peak level of the Mach wave at a 10 kHz sampling rate. Some more tests have to be done with a 80 kHz sampling rate in order to determine if the technique is good or not.

Those two techniques will be further tested on real data in the next months.

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