PILAR Acoustic Gunshot Detection & Localization system: Principles of acoustic localization of small caliber gunshots.

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Introduction

Battlefield applications of acoustic are not recent, as the first reported artillery location devices using acoustics are dating from WW1. However the potential of these techniques was only boosted recently thanks to the availability of digital processing techniques of audio signals.

Purely passive by nature, and intrinsically inexpensive in mass production, the acoustic surveillance technology presents a considerable potential for attended or unattended ground as well as for embarked sensors. The particulars of army actions theatres from the 80's have given priority to the monitoring of cease-fire agreements and the protection of the forces engaged in peacekeeping operations against sniper fire.

The purpose of this paper is to expose the basic principles of acoustic gunshot localization embedded in the PILAR products from METRAVIB R.D.S.

Simplified acoustic model

A small arm yields mainly two distinct acoustic waves were a fire is issued: the muzzle blast (MB) and the shock wave (SW) or Mach wave. The MB is generated by gas expansion after fire at the mouth of the weapon. At large distance from the shooter (hundred of meters typically), the MB acoustic signature exhibits mainly a low frequency spectral content (typically below 500 Hz). The SW is generated by the supersonic speed of the bullet and is characterized by a typical N shape acoustic signature [1] as shown on figure 1 below and exhibits high frequency spectral contents when compared to MB.

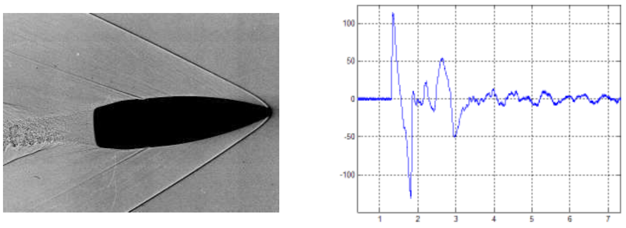


Figure 1 : Schlieren visualisation of a shock wave generated by a supersonic bullet (left) and typical acoustic signature measured at a miss distance of 75m for a 14.5 mm calibre (hor. axis : 1 ms/div; vert. axis : 50 Pa/div).

As depicted in figure 2, the MB may be considered as a spherical sound source in free field conditions whereas the SW may be approximated by a distribution of monopoles along the trajectory of the bullet and exhibits a conical wavefront.

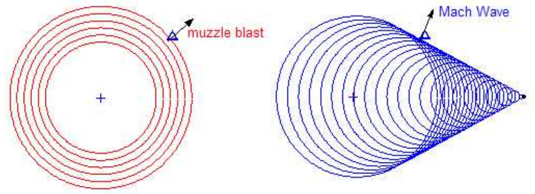


Figure 2 : illustration of spherical wavefront for muzzle blast (left) and conical wavefront of the Mach wave (right). The arrow indicates the wave vector.

To establish the simplified model, we consider the geometry depicted on figure 3 for an ideal bullet travelling at constant speed (*i.e.* without deceleration along trajectory).

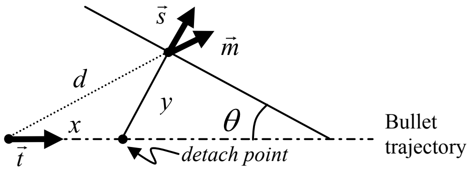


Figure 3 : geometry of the fire.

Denoting by $\vec{t}$, $\vec{s}$ and $\vec{m}$ the unit norm vectors of respectively bullet trajectory, SW wave vector and MB wave vector, one may write

$$d\vec{m}=x\vec{t}+y\vec{s} \ , \tag{1}$$

where d is denotes the shooter distance, x the distance between the shooter and the *detach point*, and y the distance from the detach point to the acoustic receiver. The opening angle θ of the shock cone is such that $\sin\theta=c/v$ and may be expressed by the relation

$$\vec{t}.\vec{s}=\frac{c}{v}=\frac{1}{M} \tag{2}$$

Where M is the Mach number, c the sound velocity and v the bullet speed.

Estimation of shot parameters

When using a single array, capable of measuring both the acoustic signature and the wave vector, the azimuth of fire location may be estimated from the measurement of muzzle blast wave front. In addition, the difference in time of arrival between the SW and the MB may be expressed as

$$\Delta t=\frac{d}{c}-\left(\frac{x}{v}+\frac{y}{c}\right) \tag{3}$$

Using (1) and (2) to replace y in (3), the distance to the shooter may be estimated by

$$d = \frac{c\Delta t}{1 - \vec{m}.\vec{s}} \tag{4}$$

This surprisingly simple results shows that the distance to the shooter may be estimated by a joint measurement of time of arrival (between MB and SW) and of wave vectors.

The bullet trajectory $\vec{t}$ cannot be estimated when using a single acoustic array because the bullet speed is unknown. One may replace this unknown parameter by some average speed calculated for a large panel of calibres, but even in this case the trajectory is ambiguous since eq. (2) has two solutions in a 2-D plane (ambiguity may be removed if MB is available).

At least two acoustic arrays have to be used to unambiguously estimate the bullet trajectory. Indeed, denoting by $\vec{s}_1$ and $\vec{s}_2$ the SW wave vector, and assuming $\vec{s}_1 \neq \vec{s}_2$ (i.e. the bullet passes in between the acoustic arrays), it may be deduced from (2) that

$$\vec{t} = \frac{\vec{s}_1 + \vec{s}_2}{\left\| \vec{s}_1 + \vec{s}_2 \right\|}, \tag{5}$$

and the bullet speed may also be estimated by using (2).

Description of PILAR system

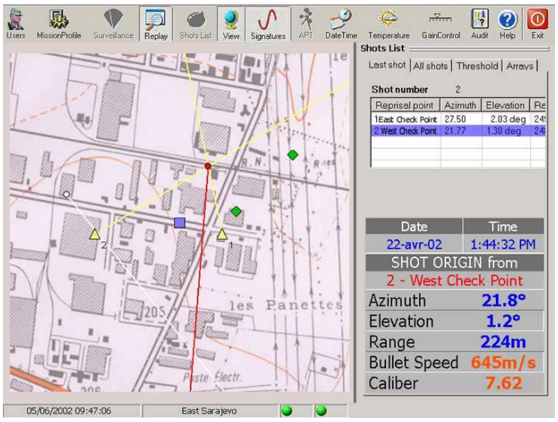
PILAR system is a state-of-the-art acoustic device dedicated to detection, localization and classification of light caliber gunshots. It is composed of one or two acoustic arrays, a compact signal processing unit, and a laptop unit for the display of results (see figure 4). An optional observation turret is also provided and may be may be connected to PILAR system to provide a picture of the origin of the shot in real time.

Figure 4 : PILARw system (left) composed of one (or two) tetrahedral antenna(s), a processing unit and a ruggedized display unit (laptop) and optional observation turret (PIVOT system, photo on the right).

The processing unit first performs the detection / recognition of acoustic events (MB or SW) and estimates the associated wave vector using the 4 microphones of the tetrahedral antenna.

An homogeneous fusion of the acoustic events is then performed to estimate shot parameters. This fusion is based on the estimation scheme described in the previous section but it encompasses a large number of refinements to deal with a more complex ballistic model (non constant bullet velocity) as well as to take into account missing events, redundant information or estimation errors for each measured parameter.

Figure 5 below shows a typical display interface and table 1 summarizes the performances that have been estimated from a large number of shots (fire configuration, calibre, bullet type) and for various environments.



Shot number 2

Reprisal point	Azimuth	Elevation	Re
1East Check Point	27.50	2.03 deg	24
2 West Check Point	21.77	1.30 deg	24

Date	Time
22-avr-02	1:44:32 PM

SHOT ORIGIN from
2 - West Check Point

Azimuth	21.8°
Elevation	1.2°
Range	224m
Bullet Speed	645m/s
Caliber	7.62

05/06/2002 09:47:06
East Sarajevo

Figure 5 : Example of display interface.

The difference in accuracy when estimating azimuth or elevation is related to both the shape of the acoustic array and the fact that most of the shots recorded in the database were measured at low elevation angle.

Accuracy	Azimuth	± 2°
	Elevation	± 5°
	Range	± 10% up to 200 m ± 20% up to 600 m ± 30% up to 1200 m
Detection range		> 1500 m (environment dependant but above effective range of the weapon)
Detected calibres		5.56 to 25 mm

Table 1: Summary of performances (using 2 arrays).

Conclusion and perspectives

The basic principles of acoustic gunshot localization have been presented for a simplified ballistic model. It has been shown that increasing the number of acoustic arrays is required to better estimate the shot parameters. For this reason, new developments are focused on the simultaneous use of networked acoustic antenna, as well as on multi sensor data fusion to increase localization performances.

References

[1] Stoughton, R., Measurements of Small Caliber Ballistic Shock Waves in Air. J. Acoust. Soc. Am., 1997, **102** (2), 781-787.