Acoustic Detection and Localization for Defense and Security Applications

PACS: 43.28.Mw, 43.28.Fp, 43.28.Js

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ABSTRACT
Ground acoustic/seismic sensor platforms can be used for various defense and security applications: for battlefield surveillance as well as for border protection, or perimeter surveillance (Fig. 1). The detection of vehicles or helicopters, which are continuous noise sources and of snipers, mortars or artillery guns, which are impulsive sources, has been studied intensively during the last years. Now the most challenging task is to develop new systems enabling capabilities for urban operations.

INTRODUCTION
In the past, acoustic sensors were used efficiently in open terrain to alert, detect, track and/or classify approaching military vehicles such as tanks, helicopters and aircrafts at reasonably long ranges in a variety of environmental conditions. This is due to the fact that acoustic waves emitted by military vehicles can propagate over long distances even if there are obstacles between the source and the Non Line-Of-Sight (NLOS) acoustic sensors. For long-range acoustic propagation, numerical modeling techniques and simulations can be used to analyze and interpret experimental results and also to predict typical acoustic sensor performance in different environmental conditions.

VEHICLE DETECTION AND LOCALIZATION
Acoustic arrays
The acoustic and seismic signals emitted by land vehicles exhibit specific patterns, allowing the definition of typical signatures. Spectral lines corresponding to the engine combustion cycles and to the impact of the track parts on the engagement wheel and on the road (or from the tread pattern of tires) are easily detected. The surveillance of an area is envisaged by means of networked acoustic arrays distributed over the area of interest (Fig. 1, [1]). This picture illustrates, for 3 arrays, the detection events occurring during a typical run and the plot of the...
corresponding DOA (Direction Of Arrival) of the acoustic waves. The region of intersection of
these rays corresponds to the position of the vehicle(s).

**Acoustic propagation modeling**

The propagation of acoustic waves has been intensively studied, due to environmental
considerations (traffic noise, airport noise), and to its interest in terms of military applications [2].
Generally speaking, our sensors are placed on or near the ground and are operational at
audible or near-audible ranges (50-500 Hz). The detection is deduced from the simulations by
using equation (1) (in dB).

$$\text{NSE}_{\text{local}} + G > DT \quad \text{with} \quad \text{NSE}_{\text{local}} = \text{NS}_{\text{source}} - \text{Att} - \text{BF}$$

(Eq. 1)

where:

- $\text{NS}_{\text{source}}$: acoustic level at the source
- $\text{NSE}_{\text{source}}$: emergence of the acoustic level (on the site of the sensor)
- $\text{Att}$: attenuation due to the source-sensor propagation
- $G$: gain of the sensor system (amplification, array gain, etc.)
- $\text{DT}$: threshold level of the detection system
- $\text{BF}$: acoustic level of the background noise

From a sensor development point-of-view, optimizing the acoustic sensing performance
requires long-term R&D (Research and Development) efforts in three complementary directions
corresponding to some of the terms of the previous equation (1):
- documenting the source characteristics ($\text{NS}_{\text{source}}$),
- analyzing the environmental impact on the signal propagation ($\text{Att}$),
- improving the sensing technology ($G$, $\text{DT}$).

For the numerical estimation of the attenuation ($\text{Att}$) due to the acoustic propagation in the
atmosphere, we used two pre-existing models (ray tracing and FFP [3]) validated during
previous studies (their results were verified within the framework of cooperative benchmarking
[4]). These models are 2.5 D, which means that the calculations are made in successive vertical
planes. The data in a horizontal plane (on the ground for example) is reconstructed after an
angular scan over 360° around the source (Fig. 3). Provided that realistic meteorological profiles
for the wind and the temperature are used, as well as relevant parameters for the acoustic
properties of the soil, the results of the simulations are in good agreement with the experimental
results.

![Figure 2.- Map of the calculated acoustic attenuation superimposed on an aerial view of the site](image)

**WEAPON FIRING DETECTION**

In recent military conflicts the battlefield has shifted from open terrain to urban terrain settings.
Accordingly, acoustic sensor research and studies have been initiated in our national programs
and in international ones with more emphasis on the current weapon firing threats.
Internationally, we participated in the NATO Task Group 53 (TG-53) to evaluate acoustic
sensing capabilities for the detection and localization of direct weapon firings (e.g., snipers and
RPGs) and indirect weapon firings (e.g., mortars and artillery) [5].

**Mortar detection**

The detection and localization of artillery guns on the battlefield is envisaged by means of
acoustic aerial waves including sonic and infrasonic waves. During experimental trials we saw
that it is possible to detect and localize various artillery guns and mortars up to distances of a few kilometers by deploying a system of acoustic UGS [6].

Fig. 3 shows the spectrograms of an acoustic signal recorded from one of the acoustic sensors. The vertical lines correspond to high-energy impulsive events. The first one corresponds to the Mach wave of the projectile, the second one to the muzzle wave (the time of this event is the time of departure of the projectile) and the last one to the detonation of the high-energy projectile after its impact on the ground.

The directions of arrival of these waves are calculated by using the times of arrival of these impulsive events. Fig. 3 presents, superimposed on an aerial view of the site, the visualization of the direction of arrival of the wave coming from the weapon and from the detonation of the projectile for two antennas (red dots). The junctions between these lines give the estimated positions of the gun and of the impact of the projectiles which are close to the real positions (blue dots).

**Modeling of the propagation:** The atmospheric refraction due to the vertical gradients of the wind and of the temperature has a major influence in the case of low-frequency, long-range propagation. As the small relief features and obstacles are negligible at low frequencies, the ground was considered to be flat for these simulations. For a short stand-off, acoustic levels decreased with the distance of propagation. For long-range detection, more complicated situations occurred, with, for example, an acoustic shadow zone shrouding some of the deployed beacons, followed at longer range by a zone where the sound was refracted by some high-altitude layers of the atmosphere (Fig. 4). This in some directions a “gap” was observed on the cartography of the sound. Operationally, it means that the number of the sensors deployed on a given area has to be larger in order to guarantee that enough sensors give “positive detections” (i.e. outside a shadow zone).

**Sniper detection**
Some recent military actions (Bosnia, Somalia, Afghanistan, Iraq, etc.) have highlighted the fact that snipers are a threat to the army forces. Among the potential systems of detection, acoustics is a technique which can help to build a solution. Acoustics can be used alone or in conjunction with other techniques like radar or infrared. First prototypes have been studied since the 90s and have resulted in the design of various systems in France as well as in other countries.
The objectives are to detect and to localize the sniper with a network of acoustic macrosensors, i.e. to determine the local bullet trajectory and the origin of the round. The use of acoustics for such a system can be easily explained if one considers the capability of acoustics to detect the sound sources in all directions, and the high acoustic level of the waves generated by a shot. The pressure and the time characteristics of the Mach wave generated by a supersonic bullet associated with the characteristics of the muzzle wave caused by the combustion of the powder are the main information used for this purpose. A complete localization is conducted after the triangulation of the azimuth and elevation estimated by 2 or 3 macrosensors.

**Modeling for impulsive sources:** Numerical simulations of impulse sources like the detonation of a high explosive charge (blast wave) or the muzzle wave generated at the exhaust of an artillery gun necessitate the creation of experimental data bases concerning the real pressure signals measured near the source or the use of pseudo-empirical models. The Friedlander equation (Eq. 2 and Fig. 5) is one of these classical models which needs only three parameters: the peak value of positive overpressure \(p_+\), the duration of the positive phase \(T_+\), and a decay factor \(\alpha\).

\[
\Delta p(t) = p_+ \left(1 - \frac{t}{T_+}\right) e^{-\frac{t}{T_+} \alpha}
\]  

(Eq. 2)

With such analytical models it is easy to calculate the influence of the various physical parameters. For example, if we consider three theoretical signals differing from one another only on the value of the duration of the positive phase and we calculate their power spectrum, we can see that the maximum of the energy content decreases if the impulse is shorter (Fig. 5). At the same time the frequency corresponding of this maximum increases but the slopes of these spectrums are parallel for low frequencies and are asymptotically the same for high frequencies.

![Figure 5.- Theoretical signal and spectrum of a typical blast wave](image)

**Modeling for sniper detection:** The modeling of sniper detection systems requires a much more complicated approach than the modeling of detection systems based on continuous noise. Here we have two acoustic sources, the muzzle of the gun and the bullet during its flight. These two sources have to be modeled (concerning the muzzle wave see the previous paragraph), at first intrinsically, then after the propagation corresponding to the paths between the source and the receptors (microphones). The principal terms used to describe the effect of the propagation are the absorption by the atmosphere, the reflection on the ground (or vegetation) and on other surfaces like hills, walls, etc. In some cases, the diffraction by obstacles and the refraction by a layered atmosphere are also relevant. Then the synthetic signals can be simulated for each of the individual positions of the microphones of the system.

**URBAN CONFIGURATION**

During the year 2006, the STAT (Service Technique de l'Armée de Terre) offered ISL the opportunity to carry out some measurements in an urban environment in the OKA village of Lehnin (Germany). Thanks to the measured signals, we were able to test our classification and localization algorithms, especially the stand-alone algorithm designed for the estimation of the shooter/array distance with one helmet array only. These tests were relatively intensive: Seven
firing positions were used and the helmet array was positioned in four different places, at different distances from the walls (varying between ten centimeters to five meters). Two hundred shots were fired, including multiple-shooter scenarios.

**Helmet for the land warrior**

The presence of snipers in modern conflicts leads to high insecurity for the soldiers. For this reason we are working on a system integrated into the head equipment of the soldier. An array of microphones has been built in the helmet: in this configuration, the sensors will always move with the user of the helmet.

The best performance will be obtained by gathering the information coming from systems worn by several soldiers. Nevertheless, for example in the case of transmission failure between the warriors, it is important that each soldier should be capable locally to acquire and process a maximum of information, even if a stand-alone configuration is less accurate. That is why our first priority is to study the various parts of the signal processing algorithm used locally (for each soldier). The localization of the detected waves is achieved using classical array signal processing techniques adapted to our configuration: the algorithm estimates the time of arrival of the detected Mach wave on each microphone and calculates the Direction Of Arrival (DOA) of the wave. The beamforming method is used for the localization of the muzzle wave. Once the estimation of the DOA of the muzzle and Mach waves has been performed, it is possible to evaluate the caliber of the bullet, the miss distance and the shooter/array distance.

**First experiment in an urban configuration**

The stand-alone computation algorithm gives good results concerning the estimation of the shooter/array distance and the caliber [7]. The standard deviation of the estimate is less than 20% of the true shooter/array distance. This means that the designed algorithm is efficient as long as input parameters are valid. Among these parameters, the duration of the N-shape of the Mach wave has a great influence. The results show that an 80 kHz sampling rate is sufficient for a good estimation of the N-wave characteristics. For example, on Fig. 6, nine shots were detected at different times of the day.

The first results obtained in an urban environment are encouraging. Even if the algorithms used in this context were not designed to deal with the multiple reflections occuring in this environment, 50% of the shots were perfectly localized. This means that the direction of arrival of the shot was detected and the shooter/array distance, the caliber and the miss distance were correctly estimated with one array only (one helmet). The cause of these bad results has been determined: they are mainly due to the presence of multiples reflections in the acoustic signals, leading to a bad classification of the Mach wave, and to a bad detection or bad localization of the muzzle wave (in most observed cases). In a few other cases, the signal to noise ratio of the muzzle wave was lower than expected, inducing some difficulty in estimating the time of arrival of the wave.

![Figure 6.- Research prototype of a helmet equipped with an array of microphones and aerial view of the site showing the direction of the various detected events](image)

**Modeling**

As the experiments in an urban configuration are much more restrictive and difficult to organize, we have improved our simulation model to take into account the reflection of the blast waves and of the Mach waves on vertical walls. The theoretical work of Clay, Chu and Li [8] is used to calculate the reflected wave corresponding to a reflection on a wall with finite dimensions and issuing from a point source (Eq. 3 and Fig. 7). We have adapted this approach to the case of a
wall perpendicular to the ground (wall of a building). The expression of the Helmholtz-Kirchhoff integral is:

\[ P(f) \approx BR_{12}^2 \int \frac{e^{-ik(R + R_s)}}{RR_s} dS, \]  

(Eq. 3)

where \( k \) is the wave number, \( B \) is a constant having the dimensions of a pressure, \( R_{12} \) is the reflection coefficient, \( \frac{\partial}{\partial n} \) is the derivative normal to the wall surface and the distances \( R \) and \( R_s \) are defined in Fig. 7. The results obtained (blue curve) are in a good agreement with the experimental results (red curve) and better than those provided by the classical equation of a reflection on a semi-infinite surface.

![Figure 7.- Schematic of the configuration and example of results (blast wave on a limited wall)](image)

CONCLUSIONS

This paper describes different applications where the acoustic detection and localization of noise sources are of major importance in today’s Defense and Security needs. In the domain of Intelligence, Surveillance and Reconnaissance (ISR), acoustic sensing provides a low-cost, passive and omnidirectional assessment of the environment. This is particularly true for threats characterized only by transient events like small-caliber and artillery shots.

In an urban environment, the direct wave is often superimposed on the reflections due to the walls of the houses, inducing challenging conditions for signal processing techniques. In 2008 we plan to participate in common field experiments whose purpose is to conduct comparative studies of the acoustic propagation of weapon firing events. Improvements in the scientific knowledge of these specific conditions as well as in the performances of the detection systems are expected.

Acknowledgements: Our special thanks to all the people involved in the previous NATO common field trials: to the US Army YPG and ARL members for hosting the experiments of mortar detection in Yuma, Arizona and to the French DGA/ETBS members for hosting the vehicles detection experiment in Bourges, France.

References: