Transient acoustic detection for hostile fire indication for helicopters

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Transient acoustic detection for hostile fire indication for helicopters

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ABSTRACT

The goal of this experimental research is to determine the potential of pure acoustic detection for hostile fire indication for helicopters, while guarantying a very low true false alarm rate in the case of high helicopter speed, large helicopter-bullet distance range and small calibres. An integration into a multi-sensor system, could provide a fully embedded, defence-feature technology capable of immediately alerting a helicopter crew that even a small projectile has closely passed by their machine, and provide an indication of the bullet trajectory. This article summarizes the design, the test in real-flight situation, and the performance results of an experimental acoustic array demonstrator developed for this purpose and evaluated for a referential of situations of 4 small arms firings with calibres from 5.56 mm to 12.7 mm and a total of 592 firings ×52 flight exposure situations (altitude, hover, speed, orientation). The detection system is an experimental planar, centimetric, acoustic array recording unit designed for low sensitivity to laminar and turbulent air flow, rear pressure and vibrations and high acoustic selectivity. This is combined with a transient signal post-processing solver that is implemented as a deterministic cost minimization function. The conclusion of the research is a strong confirmation of the feasibility of an under-helicopter acoustic detection of small calibres hostile firings as well as the proposal of a general performance law for the capability of such a system to detect small calibres, including passing-by distances of up to several hundreds of m and speeds of up to 120 kn.

Keywords: Hostile fire indication, transient signals, shooting, helicopter, small calibre, acoustic array, acoustic solver, acoustic inlet, acoustic shockwave, acoustic muzzle blast, acoustic propagation, Fermat point.

1 INTRODUCTION

The scope of the present research is to demonstrate the potential of acoustic detection of hostile fire against helicopters by means of an experimental embarked flush-mounted small-size antenna, adapted to the cargo bay of a test-helicopter.

The article briefly describes the design of the experimental system, the developed solver, the integration of the hardware unit in a Cougar test helicopter, and the results of an extensive field-trial for 4 small arms firings with calibres from 5.56 mm to 12.7 mm, a total of 592 firings × 52 representative flight situations. This field-trial was defined after a first phase study, in which measurements of long-range individual weapons were performed, which allowed the assessment of their acoustic signature and their variation within a certain range for 520 firings × 41 flying situations for the same weapons. The cited report distinguished between two main sources: the “blast noise” emitted by the gun (muzzle blast, MB), and the “shockwave noise” caused by the bullet passing its target at supersonic speed (SW). The research focused on the SW signal. This is considered as a more reliable signature, since the smaller the miss-distance (so the higher the danger), the higher the energy of the acoustic signature is. The main difficulty encountered during these experiments was the limited signal-to-noise ratio (SNR), estimated between -5 and +15 dB from the experimental data. Conversely, the maximum SPL measured by microphones embarked under a flying helicopter was estimated through this experimental campaign at around 135 dB, a reasonable value which is compatible with many affordable technologies. Moreover, a detection algorithm has been developed based on an envelope analysis after a smooth bandpass filtering. Coherence between the different sensors was used to select significant events and estimate the direction of the “Fermat point” (FP: apparent source of the SW signal, see Figure 1). The performance evaluation of the whole measurement campaign led to the conclusion that a good detection based on the SW signals adequately estimates (15° std) the direction of the FP but falls rapidly for ranges over 100 m and flight speeds up to 80 kn. This conclusion therefore oriented the second phase towards improving the experimental platform towards higher distance (typ. 500 m) and speed ranges (typ. 120 kn).
situations of great interest for the protection of helicopters. To introduce the acoustic propagation implied by the object of this research, the next figure illustrates an in-plane schematic of the acoustic situation at the two moments of interest: first the instant when the shockwave of a bullet reaches the helicopter, and second the instant when the muzzle blast reaches the helicopter.

Figure 1. Acoustic propagation situation example (case of a lateral oblique hostile fire), at two different instants. Top: shockwave passing by the helicopter (note: the shockwave front is not spherical because of the bullet deceleration). Bottom: muzzle-blast passing by the helicopter.

2 DESCRIPTION OF THE EXPERIMENTAL SYSTEM

2.1 Concept of the solution

A preliminary study allowed to determine the basic acoustic signal processing: the detection principle was designed as a bandpass time-domain process (basically an envelope analysis after a smooth bandpass filtering) of the “shockwave noise” signal generated by a bullet passing by its target at supersonic speed. Properly capturing this signal involves a trade-off between a whole set of considerations. For the global geometry of the system, a first trade-off choice was the overall maximum dimensions of the system of at least one half of the lowest frequency of interest, and positioning six acoustic inlets of the array in-plane of a flush external face.
This subsystem is inserted into a coupling plate adequately fitted and fastened to the cargo bay opening of the test helicopter, with a proper isolation of the main body of the device from the vibrations of the supporting coupling plate as well as de-coupling the sensors themselves from the main body of the device.

Figure 2. Geometry of the acoustic array versus the wavelengths of interest

The selection of 6 sensors is the result of the targeted need. The minimum required set of sensing positions, for uniform 2D detection, is theoretically three locations creating a right-angled triangle. Adding two more sensors symmetrically to the right corner provides a 2nd order estimation, improving both accuracy and reliability: this leads to four sensors on a circle, and a central sensor. Adding a fifth sensor on the circle adds redundancy and still improves the reliability, requiring six channels while allowing detection in any direction, even with two failing sensors. Further increasing the number of sensors has marginal interest.

Once this global geometry and positioning defined, one must then consider, at a smaller scale, the design of the acoustics inlets themselves, in order to reduce their sensitivity to parasitic turbulent or vibrational contributions. Only a brief discussion about this design (see Figure 3) is presented hereafter as a detailed description would be beyond the scope of this article. As shown in Figure 3, the external array-face against which the acoustic inlets are aligned, and which is directly exposed to the flow, has been designed with a controlled roughness (instead of a smooth surface), implemented with a metallic wire mesh (hereafter named “outside mesh”). The basic idea behind this concept is that a smooth surface is not optimal for all possible flow incidences and speeds. A finite roughness is expected to behave better in several possible flight conditions, especially at higher speeds (similar to the "shark scales" concept used in other applications). The other feature of the windscreen is to average the pressure over the inlet surfaces. This is achieved by foam and a second mesh (hereafter the inside mesh) with a thinner pattern only covering each acoustic inlet (while the outside mesh covers the full antenna surface).

The outside mesh was chosen with a round wire pattern with specific diameter and opening. This mesh is expected to be strong enough to protect the sensors, while being almost acoustically transparent. It is backed by a layer of open cell foam, which helps limiting the flow entrance behind the mesh and provides a slight acoustic resistance. The surface of the sensor inlets is then again covered by the inside mesh, chosen with a smaller mesh-scale that reduces the acoustic impedance mismatch between the inlet and the surrounding array body.

In order to provide significant spatial averaging of turbulence pressure, the outside diameter of the inlet is greater than the shortest acoustic wavelength of interest, which leads to a modal behaviour of the related cavities. This is far from an “isobaric” volume and the microphone placement within such a resonant volume would not be robust. The inlet is thus based on a “dual-stage” design involving two cavities: the first one is large enough for spatial averaging, while the second one is small enough to ensure an “isobaric” acoustic behaviour suitable for robust pressure sensing. Although an improved inlet design might be considered later, the current design combines proven solutions and technologies.

The sensing microphone was finally selected in order to cope with high noise levels without saturation and to have an even response over the targeted frequency band. The array was thus equipped with pressure measurement microphones, which are rugged and designed for in situ nearfield sensing and were successfully used during previous measurement campaigns.
2.2 Design summary and practical implementation

To summarize, apart from the supporting structures the external design thus involves two coupling grids: a large external one with a small resistance to allow spatial averaging without too much low-pass filtering, and a second smaller grid pad with a higher resistance for a correct tuning of the inlet frequency response. Behind the grids, the basic principle of the dedicated inlet is to couple a large external surface to a (small) internal cavity through suitable resistive materials (screen), allowing the external pressure field to average into an internal “isobaric” pressure close to the microphone membrane. This leads to a low-pass behaviour, and has therefore been designed with the desired spectrum in mind. As the detection principle is based on differences in time of arrival, which could be significantly blurred by averaging over a large surface, there was another trade-off, still enforced by the limited size of the whole acoustic array.

Those 6 inlets are integrated into a main body, made of a heavy metal part, which is then firmly fastened on the coupling plate. Conversely, its mass may be used to prevent vibrations being conducted from the cabin walls to the array sensors. For this reason, the array assembly was mounted on elastomer mounts, which compliance combined with the array mass builds a low-pass mechanical filter. This is the first step of the vibration isolation of the array. A second isolation-step was provided by the mounting of the sensor assemblies into the array body. A flexible elastomer foam was used to fit each sensing assembly, much more compliant as their mass is relatively low and they cannot escape from the array body because of the wire meshes. This “two stage mechanical filter” proved to filter out a great part of the parasitic vibration which would otherwise have spoiled the acoustic measurements. The same principle holds for the acoustic isolation: the rear lid, built as a thick and rigid plastic part, allowed both to increase the weight of the array assembly and to protect the array from noise inside the cargo bay. It is therefore sealed by a surrounding gasket. The sensor assemblies are also carefully sealed on their rear face, providing a second step of acoustic isolation.
Figure 4. Experimental system. Geometrical typology: 6 acoustic inlets (5 \( \times \) 4 \( \times \) 3 \( \times \) 2 = 120 sub-patterns of 3 inlets), 5 peripherals (circular), 1 central (small patterns remove ambiguities, large patterns increase precision). A trade-off between redundancy (detection still fully operational in case of failure of any single microphone), and performance & precision (azimuthal accuracy and removal of ambiguities).

The flight platform was the TH-98 Cougar of the Swiss Air Force (see Figure 5). Since the HELIGUARD system for these tests was mounted on a plate built for the cargo bay, the system can in principle be fitted on any TH-98 (Cougar) or TH-06 (Super Puma) of the Swiss Air Force. The helicopter trajectory for the whole experiment is shown on Figure 7.

Figure 5. Experimental system mounted under the test helicopter.
3 MATHEMATICAL AND THEORETICAL IMPLEMENTATION OF THE HFI SOLVER

This section presents the mathematics of the implemented solving method. From a global point of view, the method is a direct deterministic calculation of the Fermat point and the P.O.O point, combined with analytical approximations (Taylor series) providing a substantial gain of computation time. The algorithm does not rely specifically on SW or MB, but uses all the information at the same time (mixed solving), and thus provides a solution returning all the trajectories that explain the timestamps (in some way a consequence of the mixed solving that allows solutions to be discriminated from other complementary measures).

The solver is not implemented on the device itself yet but can automatically post-process the captured data. The solver detects muzzle blast and/or shock wave timestamps and solves point-of-origin and line-of-fire according to the calibre that provides minimal residuals. At this time, the post-process is not fully automated, but it could technically be turned into a quasi-real-time computation, able to process incoming data streams and immediately return the detection result.

The detection situation assumes that a sniper has just fired a gun in a theatre of operation (TOO). There are several microphones in the field that possibly record muzzle blast (MB) and shock wave (SW) information. The objective is to find the location of the sniper and the firing direction, for a typical distribution of the n (n=6) microphones of the acoustic array, as accurately as possible and in a minimum amount of time. Previous internal studies have shown that an estimation of ballistic information (velocity of sound and type of ammunition) is necessary for this algorithm to obtain robust results, and first versions of a detection solver have been successfully implemented and tested.

3.1 Reverse problem: Finding the timestamps given the shot parameters

In a first step, we suppose that everything about the sniper shot is known:

- Location ($S_x, S_y, S_z$),
- Firing angle $\theta$ (trajectory is supposed to be flat),
- Time $t_0$,
- Bullet initial velocity $v_0$ and deceleration constant $k$; see Table 1 for a list of such parameters.

Without loss of generality, we set all variables but $v_0$ and $k$ to be equal to zero. In what follows, we show how to compute the time needed for the MB and the SW to reach a microphone located at position $(x, y, z)$.

Table 1. Example of bullet kinematic parameters.

<table>
<thead>
<tr>
<th>Name</th>
<th>Calibre</th>
<th>$v_0$ [m/s]</th>
<th>$k$ [1/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PGM HEC</td>
<td>12.7</td>
<td>780</td>
<td>0.5</td>
</tr>
<tr>
<td>FAS 90</td>
<td>5.56</td>
<td>915</td>
<td>1.1</td>
</tr>
<tr>
<td>AK 47</td>
<td>7.62</td>
<td>660</td>
<td>1.1</td>
</tr>
<tr>
<td>SAKO</td>
<td>8.60</td>
<td>830</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**Muzzle blasts**

In the coordinate system where the shooter stands at the origin, and writing $c$ the sound velocity, the time taken by the muzzle blast to reach a position $(x, y, z)$ is given by

$$T_{MB}(x, y, z) = \|(x, y, z)\| / c. \tag{1}$$

**Shock waves**

Since the bullet velocities are far above $c$, we can neglect the effect of gravity that is much smaller than that of the drag. For flat fires, a good approximation of the equation of motion is then

$$m \ddot{v} = -\rho \, v^2 A \, C_D / 2, \tag{2}$$

where $m$ is the mass of the bullet, $v$ its velocity, $\rho$ is the mass density of the air, $A$ is the reference area and $C_D$ is the (dimensionless) drag coefficient. This last coefficient is related to the velocity, and in the case of a Mach number greater than 1.5 it may be described by $C_D = C_{D0} \cdot (v_0/v)^n$. The exponent $n$ varies for each type of bullet, but it lies in the range...
interval \([0,1]\) and its value is typically \(n \approx 0.8\). Defining the deceleration constant by \(k = \rho v_0 A C_{D0}/(2m)\), one can rewrite the equation of motion as

\[
\frac{d}{dt} \left( \frac{v}{v_0} \right) = -k \cdot \left( \frac{v_0}{v} \right)^{n-2}.
\]

(3)

A closed-form solution exists for any value of \(n\), which then leads to the relation between the position \(x\) and the time \(t\) of the flying bullet. For instance, supposing \(x = 0\) for \(t = 0\), one finds

\[
\begin{align*}
n & = 0: \quad v = \frac{v_0}{1 + k \cdot t}, \quad t = \frac{1}{k} \left( \exp \left( \frac{k \cdot x}{v_0} \right) - 1 \right), \\
n & = 1: \quad v = v_0 \exp(-k \cdot t), \quad t = \frac{1}{k} \log \left( \frac{v_0}{v_0 - k \cdot x} \right).
\end{align*}
\]

When the sniper is not too far from the acoustic array, we can further make the approximation \(k \cdot x \ll v_0\) and find a simpler relation between \(x\) and \(t\), which has the nice property to be independent of \(n\):

\[
t = \frac{x}{v_0} + \frac{k \cdot x^2}{2v_0} + \mathcal{O}(k^2).
\]

(4)

Hence, we can compute the time needed by the bullet to reach a position \(x\) knowing only \(k\) and \(v_0\).

**Fermat point**

Supposing that the bullet travels a distance \(0 < s^* < x\) until the Fermat point, the total time needed for the shock wave to reach the microphone at position \((x, y)\) is then

\[
T_{SW}(s^*) = \frac{s^*}{v_0} + \frac{k \cdot s^*^2}{2v_0} + \frac{||(x - s^*, y, z)||}{c}.
\]

(5)

To fulfil Fermat’s principle, the location \(s^*\) must be such that \(\frac{dT_{SW}(s)}{ds}\bigg|_{s=s^*} = 0\).

Unfortunately, there is no simple formula for expressing \(s^*\). However, one can use the fact that the bullet velocity is much greater than the sound velocity and that its deceleration coefficient has limited effect on short distances. A couple of series expansions for \(c/v_0 < 1\) and \(k \cdot x \ll v_0\) around the solution for the usual shock cone leads to

\[
s^* \approx x - \sqrt{y^2 + z^2} \cdot \frac{c}{v_0} \cdot \left( 1 + \frac{c^2}{2v_0^2} + \frac{k \cdot x}{v_0} \right).
\]

(6)

Some numerical tests show that the error on the propagation time using this formula is much smaller than 0.1 [ms], which is thus negligible compared to synchronization or signal processing errors. More importantly, implementing this expression in the algorithm is much faster and more robust than performing a numerical minimization on the Fermat point.

### 3.2 Current problem

Let’s suppose that at least three microphones detect the transient sounds produced by the sniper-shot (since we want our solver to be robust in real conditions, we do not ask for all MB and SW to be detected), such that the input variables of the solver are:

- A set of MB and SW timestamps together with the corresponding microphone position: \(\{(T_{MB, i}, x_i, y_i, z_i)\}_{i=1}^{n_{MB}}\) and \(\{(T_{SW, j}, x_j, y_j, z_j)\}_{j=1}^{n_{SW}}\),
- An estimation of the bullet parameters \(v_0\) and \(k\),
- An approximate value of the sound velocity \(c\).

The algorithm then uses the ballistics model described in the previous section to find the shooting conditions \((S_x, S_y, S_z, \theta)\) that best reproduce the recorded timestamps; parameters \(v_0\), \(k\) and \(c\) are optimized to further reduce the
timestamp residuals. Ideally, only one bullet trajectory reproduces the recorded timestamps well. However, if too little information is transmitted to the algorithm, it may happen that distinct trajectories generate timestamps with the same amount of error (see next paragraphs for a mathematical description of this fact). In this case all compatible shooting conditions are returned by the algorithm, and another shot may be used later to discriminate among several sniper locations.

**Cost-function**

In full generality, we consider the following cost-function in our algorithm, which depends on the seven variables \( S_x, S_y, S_z, \theta, c, v_0, k \) and on a time offset \( \Delta T \):

\[
F = w_{MB} \cdot \sum_{i=1}^{n_{MB}} (T_{MB,i} - T_{MB}(\vec{x}_i, \vec{y}_i, z_i) - \Delta T)^2 + ...
\]

\[
w_{SW} \cdot \sum_{j=1}^{n_{SW}} (T_{SW,j} - T_{SW}(\vec{x}_j, \vec{y}_j, z_j) - \Delta T)^2,
\]

where the weights \( w_{MB} \) and \( w_{SW} \) may be related to the accuracy of the signal processing that extracts the timestamps, and where the positions \( \vec{x} \) and \( \vec{y} \) are computed in the sniper reference frame:

\[
\begin{pmatrix} \vec{x} \\ \vec{y} \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \cdot \begin{pmatrix} x - S_x \\ y - S_y \end{pmatrix},
\]

A numerical optimization is required to minimize \( F \) over the seven free variables, but one can show that the best time offset has to satisfy:

\[
\Delta T = \frac{w_{MB} \cdot \sum_{i=1}^{n_{MB}} (T_{MB,i} - T_{MB}(\vec{x}_i, \vec{y}_i, z_i)) + w_{SW} \cdot \sum_{j=1}^{n_{SW}} (T_{SW,j} - T_{SW}(\vec{x}_j, \vec{y}_j, z_j))}{w_{MB} \cdot n_{MB} + w_{SW} \cdot n_{SW}}
\]

**Step 1: Global minimization on a grid**

We define a (discrete) grid \( \mathcal{G} \) that spans the entire range of sniper locations and firing angles: the wider and the denser the grid, the more precise the results, but the slower the computation. For instance, good results are found in most cases by setting \( S_z \) to the mean value \( \bar{z} \) of the microphone altitudes and by choosing \( \Delta S_x = \Delta S_y = 50 \text{ m} \) and \( \Delta \theta = 2^\circ \). Then, based on equations (1), (5) and (7), it is straightforward to compute the value of the cost-function \( F \) on all test-points \( S_x, S_y \) and \( \theta \) of the grid; in this step the values of \( c, v_0 \) and \( k \) are given by the user and considered constant.

Looking for one single minimum of \( F \) in the grid may be enough if many MB and SW have been detected. However, this is rarely the case, so that we keep track of all local minima. Since we are interested in both the sniper location and the bullet trajectory, we first project the results on 2D-grids: at each tested position \((S_x, S_y)\) we find the firing angle that minimizes \( F \), and we denote the corresponding values by \( F_{xy} \) and \( \theta_{xy} \). We then look for all local minima of the discretized surface \( F_{xy} \), which generates a list of plausible shots:

\[
\mathcal{L}_1 = \{(S_x, S_y, \theta_i)\}_{i=1}^m.
\]

**Step 2: Local parametric minimization**

The number \( m \) of plausible shots (local discrete minima) is much smaller than the size of the grid \( \mathcal{G} \). In fact, there are in general only a few locations that are found in that way, and we can always limit this number to be smaller than a
threshold by keeping only the best points (according to the cost-function $F$). Thus, it is feasible to perform a full optimization for each plausible shot: we take each vector $(S_{x,i}, S_{y,i}, z_i, \theta_i, c, v_0, k)$ as a starting point for a numerical minimization\(^2\) of $F$, which leads to the optimized parameters:

$$L_2 = \left\{(S_{x,i}, S_{y,i}, z_i, \theta_i, c, v_0, k_i)\right\}_{i=1}^m.$$\hspace{1cm}(11)

For convenience, we assume that $L_2$ is sorted according to the cost-function: $F_i \leq F_{i+1}$.

**Step 3: Statistical test for error variance equality**

In general, we get more than one possible shot as output of the previous step, but most of the time only one such shot explains the timestamps well. In the case of several “best solutions”, they all should lead to a similar dispersion of the timestamp residuals (differences between measured and modelled timestamps). We may assume that these residuals follow a Gaussian distribution (of zero mean since they are the result of a least square minimization), so that Bartlett’s test applies: it tests the null hypothesis $H_0$ that all $m$ population variances are equal against the alternative that at least two are different. Concretely, we proceed in the following manner. If $m = 1$ we are done, only one location has been detected. Otherwise we apply Bartlett’s test on the first two sets of (smallest) residuals: if we cannot reject $H_0$ (i.e., “both variances are similar”), we add the next set of residuals to the test, so that we consider three samples. We then keep adding sets of residuals until $H_0$ is rejected (meaning that the last added shot does not belong to the final solution), or until the $m$ samples have been tested.

### 4 PERFORMANCE EVALUATION

#### 4.1 “Fire and flight” referential

In the case of an automatic detection system, just as a measurement always improves when it is related to measurement uncertainty values, the performance is worth to be qualified in terms of TF/PN matrix (True or False and Positive or Negative).

<table>
<thead>
<tr>
<th>Detection</th>
<th>TRUE</th>
<th>FALSE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shockwave</strong> (SW)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>FERMAT Point</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>“In which direction the bullet passed-by”</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Muzzle blast (MB)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DOA firing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>“In which direction is the sniper”</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P.O.O. + Trajectory + Weapon type</td>
<td></td>
<td></td>
</tr>
<tr>
<td>“where is the sniper”</td>
<td></td>
<td></td>
</tr>
<tr>
<td>“what is the bullet trajectory”</td>
<td></td>
<td></td>
</tr>
<tr>
<td>“what type of weapon”</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SW + MB</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Performance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Positive TP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Negative TN</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6. TF/PN matrix.

Since a True or a False can only be judged in relation to a situation of reference, it is convenient if not indispensable, in the evaluation of the performance of a system of detection, to decide on a very representative situation of reference to which the system can be confronted and against which the True or False decision can be judged. The performance can then be judged directly by judging the number of “True and False Positives” and “True and False Negatives”, the true

\(^2\) In practice, it is much more efficient to consider a vectorized version of $F$ and to perform a non-linear least square minimization (for instance, with the Matlab function “lsqnonlin”). It may also be desirable to restrict the ballistic parameters so that they satisfy some physical conditions, as for example $330 \leq c \leq 350$. 

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situation being known a priori since it is fully regulated by the definition of the experiment. According to this methodology, the better and completer the representativeness of the reference situation is, the more robust the quality of the performance evaluation becomes. In summary, the choice made by the project-team consisted of a flight-duration totalizing about 1h45 (all pauses deducted), including 69 flight-situations (altitude, hover, speed, orientation), all exposed to shots from 4 types of small arms (PGM HEC 12.7 mm, SAKO 8.6 mm, AK 47 7.62 mm, FAS 90 5.56 mm), and of variable and globally representative dangerousness (distance between the trajectory of the bullet and the helicopter between ~20 m and up to about 500 m), with a total of 592 firings. This situation can thus be likened to a phase of intense flight of all usual nominal phases of flight or manoeuvres close to the ground, of a long duration, during which the helicopter is subjected to a very large number of firing situations, of wide and well-distributed dangerousness, in that it covers, in close quantities, high-dangerousness firings (larger calibre and close trajectory distance), medium dangerousness firings (medium trajectory distance shots, all calibres), or low dangerousness firings (small calibres and far away trajectories).

From the point of view of detection, a natural advantage of the on-board acoustic detection solution is that the more the dangerousness increases (larger calibres, closer distances,) the more, at equal helicopter speed, the detection performance should naturally increase, because the increasingly favourable relation of the signal-to-noise ratio. Nevertheless, it can also be postulated that the sooner a detection is made, the greater its utility is, so that even the cases of low dangerousness, due to long distances, are cases of desired performance. Finally, with equal bullet trajectory and helicopter distances, since the helicopter's own noise is in itself, as a masking disturbance, a potential cause of limitation of detection capability, the cases with maximum sound disturbances such as stationary low altitude or high flight speeds, are also cases of maximum concern of this research.

Given that in the experimental design all these situations and their respective good equilibrium are taken into account, the hypothesis is made that the field-trial definition is a very representative reference, and thus, that a global statistic percentage (or a “law of capability”) of good detections according to a duration of false alarm can validly be extracted.

4.2 Shockwave detection results

In total, the experiment consists of 592 shots for 52 scenarios combining 4 different guns and various helicopter speeds, altitudes and orientations to shooting axis.

![Figure 7. GPS data of the helicopter trajectory on Tuesday, September 25.](https://www.spiedigitallibrary.org/conference-proceedings-of-spie)
Figure 8. Top: Speed 60 kn, elevation 30 m, 17 small calibre shots. Middle: Speed 100 kn, elevation 100 m, 8 small calibre shots. Bottom: Speed 120 kn, elevation 50 m, 8 small calibre shots.
The signals recorded by the 6 microphones of the antenna are processed in chunks of 1 second each, with an overlap of 50%. For each chunk, the 6 channels are synchronized to produce one signal of higher contrast (noise is supposed to occur randomly at the channels and thus somewhat cancels itself when the channels are merged, while shockwaves are added in a coherent way); an example is given in Figure 9. Then, based on all 19199 chunks that compose the whole audio recording, a logistic regression of three coefficients (STA, LTA, SNR) is performed to discriminate the shockwaves from noisy peaks in the signal. Note that the offsets used to synchronize the channels, together with the locations of the microphones, allow one to compute the direction of the shockwave propagation. The results presented in what follows, are grouped in three categories based on the helicopter speed: Low speed (lower than 10 kn); Moderate speed (between 10 kn and 90 kn); High speed (higher than 90 kn).

![Figure 9. Coherent superposition of the audio signals. The offsets used to synchronize the channels are directly related to the direction of the shockwave propagation, relative to the helicopter orientation.](image)

### 4.3 Direction of shockwave propagation results

In the case of the shockwaves, the sound originates at the Fermat point on the bullet trajectory; the knowledge of their direction of propagation thus gives some information about the bullet position at a precise time, but not directly about the location of the shooter. However, both are related, and knowledge of the former gives a good approximation of the latter. Accuracy of the detected direction of shockwave propagation is illustrated in the next figure. The accuracy mostly depends on the antenna geometry, and more precisely on its radius, and with our geometry the standard deviation of the angle error is less than 15°. For instance, about 80% of shockwave directions are measured with an error smaller than 22.5°. This means that only 20% of the detected shots would be wrongly indicated in an alarm radar indicating 8 directions. More importantly, about 98% of the times this indication would give the correct information (changing direction to fly away from the shooter, and not towards him).

![Figure 10. Accuracy of the detected direction of shockwave propagation.](image)
Figure 11. MTBFA vs. helicopter speed (top), vs. pass-by distance (middle), vs. gun type (bottom) for 592 firings × 52 flight situations.
4.4 Global results

Given the coefficients obtained by the logistic regression (three parameters STA, LTA and SNR, and one constant term), one can modify the sensitivity of the detection by varying the value of the constant. For very low thresholds, one detects all shockwaves but generates many false alarms, while for very high thresholds, the mean time between false alarms (MTBFA) is very long but many shots are undetected. The graphs of the MTBFA versus the detection rate are illustrated in Figure 11.

With a high sensitivity detection setting, i.e. acceptance of possibly one false alarm every 5 minutes (= high threat situation), the global capability is about 80% true positive detections, possibly decreasing to 60% at most unfavourable conditions (highest speeds and greater bullet passing-by distances). Globally the performance can be resumed by the three following performance indicators:

Table 2. Performance indicators.

<table>
<thead>
<tr>
<th>MTBFA</th>
<th>0-10 kn (230 shots)</th>
<th>10-90 kn (210 shots)</th>
<th>90-120 kn (52 shots)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 h</td>
<td>73%</td>
<td>55%</td>
<td>0%</td>
</tr>
<tr>
<td>30 min</td>
<td>74%</td>
<td>60%</td>
<td>0%</td>
</tr>
<tr>
<td>5 min</td>
<td>80%</td>
<td>77%</td>
<td>60%</td>
</tr>
</tbody>
</table>

A second and even more global performance characteristics indication that can be extracted from the research is the probability of detection versus the miss distance (shortest distance between bullet and helicopter), and the shooting distance (distance between shooter and helicopter). Even if for evident security reasons the field-trial conditions were limited to shootings above a ratio of 20% miss to shooting distance, the result indicates that among the 592 firings × 52 flight situations all the non-detected events are situated above a ratio of 50% miss to shooting distance. In other words, it can be extrapolated from this result that 100% of real dangerous shootings shall be detectable by the experimental system.

5 CONCLUSION

A robust and highly representative referential of situations has been recorded, including 4 small arms firings (PGM HEC 12.7 mm, SAKO 8.6 mm, AK 47 7.62 mm, FAS 90 5.56 mm), and a total of 592 firings for 52 flight situations (including high helicopter speeds and long bullet-helicopter distances, with most shots inaudible and invisible for the crew).

Among the 592 firings × 52 flight situations all the non-detected events are situated above a ratio of 50% miss to shooting distance. In other words, it can be extrapolated from this result that 100% of real dangerous shootings shall be detectable by the experimental system. In most cases the accuracy in the detection of the direction of the point of origin of a shockwave (i.e. the Fermat point) is better than 15°.

Furthermore, it can be stated that the technological demonstrator is most probably capable of detecting and localizing the point of origin of the shockwave for all the small miss-distance situations, and this with very few false alarms. At the early (less hazardous) high passing-by distances (several hundreds of m), the capability remains high.

When the helicopter is hovering, most shockwaves are detected without ambiguities and in those situations muzzle blasts can be used to confirm and make this detection more precise for distances to the shooter of up to a 100 m. At comparable passing-by distances of the bullet, the detection capabilities present low dependency on the diameter of the calibre.

In conclusion, a particularly convincing demonstrator has been developed and significant progress has been made in the domain of acoustic detection for hostile fire indication. In particular, the research increases the comprehension of the under-helicopter acoustics, the acoustics of firings from light fire-arms seen from the helicopter, and the signal processing and mathematical solving of the detection.
BIBLIOGRAPHY