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Sensitivity of shot detection and localization to environmental propagation

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ABSTRACT

Acoustic sensing systems are used to detect and localize mortar and small arm shots on the battlefield. This study is an experimental investigation on the sensitivity of the sensing performance to environmental propagation. For simulated mortar shots, the muzzle wave detection range is observed to vary by a factor of three from day to day and with the propagation direction, due to the varying atmospheric refraction. For small-arm fire shots, the shot azimuth is estimated by some degrees in an open environment, but large errors are observed for shots nearby a forest (with Mach wave reflections) in adverse atmospheric conditions. Last, the shooter's range estimate is found to feature bias and scatter. Atmospheric turbulence is found to cause the observed shot-to-shot variability of the Mach wave characteristics, which drives the scatter in range estimate. The study promotes a careful assessment of impulse sound propagation effects when analyzing, developing, evaluating and using systems for shot detection and localization.

1. Introduction

Acoustic sensing systems are relevant on the battlefield as military operations are often associated with specific acoustical signatures, e.g. large intensity, transient character. In particular, some acoustic systems have been designed to detect and localize the shots from small-arm fires and ballistic weapons (mortars, missiles, artillery, e.g. [27]). A number of such systems are available on the market (among others, the Boomerang Warrior X, Pearl, Swats/Ears and Rmgl systems are from Raytheon BBN, Acoem, Qinetiq and Uwc companies, respectively), and are operationally used to warn and protect against adverse shot threats.

The performance of these systems critically depends on the quality of the acoustic measurements and processing, i.e. on the system itself. The background noise is a factor of importance to performance. In a general sense, propagation features also tend to alter the sound signature from the source, with alterations increasing with range. A strongly altered signal cannot be sensed or interpreted. Thus propagation effects structurally pose a range limitation in the operational performance of systems. Propagation effects strongly depend on the environment. It is often discussed that the performance of battlefield acoustic sensing systems depends on outdoor environmental parameters (e.g. [18,20]). To our knowledge though, no systematic, experimentally-supported study has been proposed to categorize the relevance and relative importance of the various effects at play.

Many of the available systems are based on common physical principles, and may thus meet qualitatively comparable sensitivities to outdoor propagation. Identifying the driving physical processes for such sensitivities is of primary interest:

– For end-use, to identify the environmental conditions which tend to challenge the system performance.
– For system selection, to reach a more objective evaluation of systems and balance performances obtained in various propagation conditions.
– For system design, to understand system limitations and possibly propose innovative developments to mitigate them.

The present study is an experimental investigation to determine the environmental propagation factors that alter the shot sensing performance. It makes use of various operational acoustic sensing systems, as well as of controlled microphone measurements. These apparatus are used in various environmental conditions and with various weapon types, so to cover a more representative range of acoustic sources and propagation environments. The systems performance in shot detection and localization is analyzed in light of the changing propagation effects.

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The study is composed as follows. Section 2 briefly introduces the principles of shot detection, azimuth-localization and range-localization, and discusses the propagation effects of potential impact to their performance. Section 3 investigates the detection performance for mortar-like shots in an open environment. Section 4 extends the analysis to azimuth-localization performance and also investigates supersonic projectile shots in a near-forest environment. Section 5 discusses the sensitivity of range-localization in an open environment. Section 6 discusses the observed shot-to-shot variability in the measurements. Section 7 summarizes the results and presents some perspectives.

2. Shot detection and localization

The battlefield acoustic systems tested in this study are arrays of microphones. The size of the arrays and the characteristics of acquisition are designed to match the acoustic wavelengths of interest from the considered threats, while minimizing reflections from the supporting frame. Hand-sized and foot-sized systems are typically for personnel and vehicle operation, respectively. The microphones are synchronized and communicate to the processing unit via wire connections.

Beyond the array-structure, the tested systems share a comparable approach to shot detection/localization. They sense and process the time series of the acoustic pressure as measured by the microphones. The basic signals reaching a sensing system after a shot are well-known (Fig. 1). The gun muzzle wave appears as a spherical wave. If a supersonic projectile is shot, the passing bullet emits a conic, N-shaped Mach wave. The Mach wave is of much higher frequency than the muzzle wave.

The algorithmic processing consists in interpreting these events. Shot *detection* is usually obtained as the signals exceed a signal-to-noise ratio. Differences in the time of arrival of the muzzle wave on the microphones inform on the angle of arrival. With e.g. a straight-line assumption on the propagation path, one obtains the *azimuth* of the shot origin from the system. With a detectable Mach wave, a further processing can be used to estimate the shooter *range* from the system. Among others, the standard calculation uses some relationships between the N-shaped Mach wave characteristics and the caliber and speed of the bullet as it passes nearby the system. Range and azimuth provide the localization of the shooter relative to the system. Further information on the weapon type, ammunition type, etc might be obtained from other signal characteristics.

From the above qualitative description, the following propagation effects can be relevant to the performance of the considered systems:

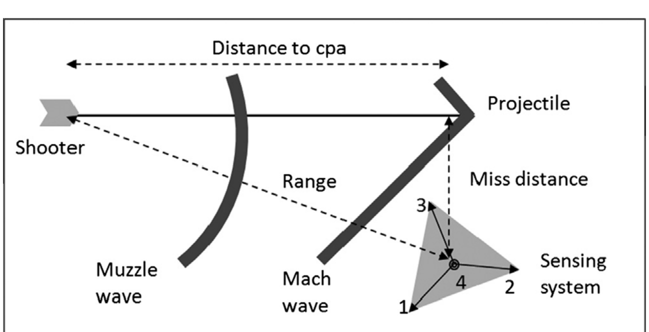

Fig. 1. Sketch of supersonic projectile shot, with acoustic sensing by a microphone antenna (microphones are numbered). Here the axis from microphones 3 to 2 is approximately aligned with the propagation direction of the Mach wave (hereafter longitudinal direction). The closest point of approach (cpa) refers to the location at which the projectile is closest to the system. The sketch is not at scale.

- Geometrical dispersion of the signal causes a general fading of the signal-to-noise ratio with the propagation range. Thus, whatever the system, a sound source is not detectable beyond some range. This effect is constant with time and location.
- In the vicinity of high-amplitude acoustic sources, interactions between the sound wave and the atmosphere take place, with interactions between the various frequencies of the signal. This non-linear propagation is relevant to the formation and short-range propagation of the Mach wave. The understanding and prediction of these effects are an area of research (e.g. [16]).
- Absorption and molecular relaxation by atmospheric gases cause an attenuation of high-frequency components of the signal with range. They modulate the Mach and muzzle waves (e.g. [6,1]). These effects depend on the concentration of atmospheric gases, which in turn depend on the time and location.
- Reflection and absorption on the ground. For a transient sound source, a receiver is reached by a direct contribution and by the ground reflected counterpart. The characteristics of the latter depend on the ground characteristics (layering, thickness, etc). This dependence has been a topic of long-standing investigations [2,4].
- Obstacles and topography cause the formation of reflected and diffracted components to the acoustic wave field, and of shadow zones in which the acoustic signals are largely decreased. These effects depend on the acoustic wavelength and on the dimensions of the obstacle. Diffractions and reflections combine in a complex manner in dense environments (e.g. forests, towns, e.g. [3]).
- Refraction stands for a deviation of the wave propagation direction due to a spatial heterogeneity in effective acoustic refractive index. Such heterogeneities are driven by wind, temperature and humidity gradients in the atmosphere. Refractive effects take two forms: (i) mean acoustic refraction relating to atmospheric stratification, and (ii) sound scattering related to turbulence. Turbulence also alters the coherence of signals, i.e. it decreases the correspondence between signals at the microphones of the antenna. The description of turbulence effects is still a challenge (e.g. [9]).
- Last, the convection of the acoustic wave relates to its displacement with the atmospheric wind. This causes some lags on the times of arrival and some changes in the apparent frequencies of the source.

The present study aims at investigating which among these processes significantly alter shot detection and localization.

3. Shot detection

The experiment discussed in this section investigates how far one sensing system detects an experimental proxy for mortar shot. It was performed in July 2012. The sound source emitted a muzzle-like wave, with no associated Mach wave. Table 1 gives an overview of the experiment. The location was in a large, flat field with 2.5 m-high corns in Alsace, France. The field was homogeneous except for a 6 m-wide North–South path. Measurements were performed on three days of July 2012 with distinct weather features. A meteorological station monitored the outside temperature and horizontal wind at a height of 2 m.

The acoustic source was a gas cannon explosion, emitted every 36 s. The maximum pressure level typically reached 1250 Pa; the signal was reproducible by 10%. The cannon main tube was set vertically so that the emission was horizontally isotropic. The test used a vehicle-version of a commercially available shot detection system. It was here used on a tripod to avoid interference with a vehicle structure. The system was composed of a 4-microphones