Acoustical Characterization of Gunshots

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***Abstract*- This paper addresses several practical and theoretical issues encountered in the analysis of gunshot audio recordings. Gunshot recordings have the potential for both tactical detection and forensic evaluation. Such recordings can provide information about speed and trajectory of the projectile, the estimated location of the shooter, and in some cases the type of firearm and ammunition used. However, audio recordings of gunshots typically contain background noise and reverberation due to the gunshot sound reflecting off and diffracting around nearby surfaces, and these effects may limit the reliability of the acoustic estimates. Recordings obtained under carefully controlled conditions are used to demonstrate several key features and limitations of acoustic gunshot analysis.**

I. INTRODUCTION

Criminal, terrorist, and military actions involving firearms are of increasing concern to police, soldiers, and the public. A variety of commercial and experimental acoustical detection and classification systems designed for gunshot sounds are available. These systems can be intended to detect acoustical "gunshot signatures," to classify or identify specific firearm types, and to detect and localize snipers. The degree to which a system can achieve satisfactory performance is typically limited by the assumptions required to estimate the firearm and/or projectile behavior based on the available acoustic evidence.

Assessing and evaluating acoustic gunshot detection systems requires a thorough understanding of the characteristics of gunshot sounds and the significance of sound wave reflection, absorption, and diffraction from the ground, buildings, and other nearby objects.

A. Muzzle Blast

A conventional firearm uses a confined explosive charge to propel the bullet out of the gun barrel. The sound of the explosion is emitted from the gun in all directions, but the majority of the acoustic energy is expelled in the direction the gun barrel is pointing [1-5]. The explosive shock wave and sound energy emanating from the barrel is referred to as the *muzzle blast*, and typically lasts for less than 3 milliseconds. The muzzle blast acoustic wave propagates through the air at the speed of sound (e.g., 343 m/s at 20°C), and interacts with the surrounding ground surface, obstacles, temperature and wind gradients in the air, spherical spreading, and atmospheric absorption. If a recording microphone is located close to the firearm, the direct sound of the muzzle blast is the primary acoustical signal. On the other hand, if the microphone is located at a greater distance from the firearm the direct sound path may be obscured and the received signal will exhibit propagation effects, multi-path reflections, and reverberation.

Some handguns and rifles can be equipped with an acoustic suppressor. Suppressors are designed to reduce the audible report (and often the visible explosive flash) of the muzzle blast to reduce the likelihood of detection and/or to prevent hearing damage. Thus, gunshot acoustical detection systems that rely on the muzzle blast must accept the possibility of suppressor use by clandestine individuals.

B. Mechanical Action

For some firearms the sound of the mechanical action may be detectable. This includes the sound of the trigger and hammer mechanism, the ejection of spent cartridges, and the positioning of new ammunition by the gun's automatic or manual loading system.

The mechanical action is, of course, generally much quieter than the muzzle blast and projectile shock wave, so this acoustical signal is only relevant if the microphone is located close enough to the firearm to pick up these subtle, telltale sounds. For example, personal surveillance recordings or recorded phone conversations that take place in proximity to the shooter may contain this information.

C. Supersonic Projectile

In addition to the muzzle blast and mechanical action, a third source of acoustic gunshot information is present if the bullet travels at supersonic speed [3, 4, 6]. The supersonic projectile's passage through the air launches an acoustic *shock wave* propagating outward from the bullet's path. The shock wave expands in conic fashion behind the bullet, with the wave front propagating outward at the speed of sound. The shock wave cone trailing the bullet has an inner angle, $\theta_M = \arcsin(1/M)$, where $M = V/c$ is the *Mach Number* (V is the bullet's speed, and c is the local speed of sound). θ_M is referred to as the *Mach Angle* [1]. The geometry is shown in Fig. 1.

The speed of sound (c) in air increases with increasing temperature:

$$c = c_0\sqrt{1+\frac{T}{273}} \qquad (1)$$

where T is the air temperature in degrees Celsius and c_0 = 331 m/s is the speed of sound at 0°C. For each degree Celsius increase in temperature, the speed of sound increases by approximately 0.61 m/s.

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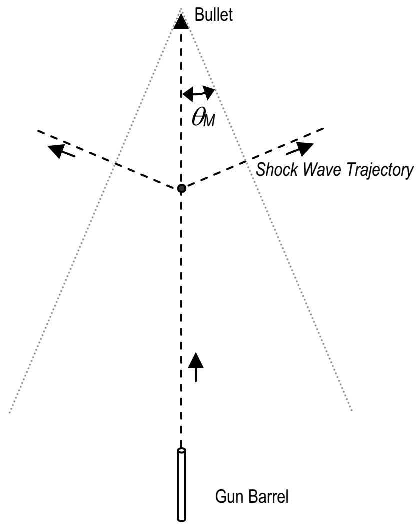

Figure 1. Shock wave geometry for a supersonic projectile. The Mach Angle θ_M is small for $(V/c) \gg 1$, and close to 90° for $(V/c) \approx 1$.

If the bullet is traveling substantially faster than the speed of sound, the Mach Angle is small and the shock wave propagates nearly perpendicularly to the bullet's trajectory. A bullet traveling only slightly faster than the speed of sound has a Mach Angle approaching 90°, meaning that the shock wave is propagating nearly parallel to the bullet's path. Moreover, as the bullet slows along is path due to friction with the air, the corresponding Mach Angle widens down range.

D. Surface Vibration

Acoustic vibration may also be carried through the ground or other solid surfaces. The sound of gunshots, ordnance explosions, and similar impulsive sounds can cause detectable vibratory signals propagating through the ground many tens of meters from the source. Sound propagation in rock and soil is typically at least 5 times faster than the speed of sound in air, so calculations to correlate surface vibratory motion and the subsequent airborne sound arrival may be productive.

In summary, the primary acoustical evidence available from a gunshot can include the muzzle blast, the projectile shock wave for supersonic bullets, and possibly the sound of the firearm's mechanical action and ground vibration, if the microphone is sufficiently close to the gun.

II. Analysis of Gunshot Recordings

The acoustical characteristics of several representative gunshots with supersonic projectiles are shown in Figs. 2-5. The signals were obtained using two high quality omnidirectional audio recording microphones (DPA 4003), a corresponding high voltage preamplifier (HMA 5000), and stored on digital audio tape with 16-bit resolution and a 48 kHz sample rate per channel. The microphones were mounted 30 cm apart and 1.6 meters above the sandy but firm (frozen) ground surface of a firing range.

A. Example Gunshot Characteristics

Fig. 2 shows the recorded acoustic data for a Winchester 308 rifle fired horizontally toward the microphones at a distance of approximately 9 meters.

The bullet speed (V) for the particular ammunition used was 2728 ft/sec (831.5 m/sec) and the speed of sound (c) was 1075 ft/sec (328 m/sec) at approximately 20°F (-7°C). The resulting Mach Number (V/c) was M=2.54, giving a Mach Angle (θ_M) of 23.2°.

The arrival of the supersonic bullet's *shock wave* at the microphones is visible in Fig. 2, first at microphone 2 and then at microphone 1, with the time delay between channels corresponding to the time required for the shock wave to propagate at the speed of sound from the first microphone to the second. The shock wave cone expanding behind the bullet reaches the microphones relatively quickly when the bullet trajectory is toward the microphones because the projectile is moving at more than 2.5 times the speed of sound. The next significant event is the arrival of the *shock wave reflection* from the ground. Note that the reflection is of slightly lower amplitude due to the ground absorption and the longer propagation path taken by the reflected energy. Next, the acoustic signature of the *muzzle blast* arrives at the microphones after having propagated at the speed of sound from the firearm position to the microphones. Finally, the *muzzle blast reflection* from the ground arrives at the microphones at a delay corresponding to the down-and-up propagation path of the reflection.

The second example uses the same ammunition but a firing trajectory perpendicular to the line connecting the microphones, passing approximately 8 meters from microphone 2. The resulting acoustic recording is shown in Fig. 3.

In this case the propagation of the bullet's trailing shock wave is essentially parallel to the path of the muzzle blast, resulting in a more nearly coincident arrival of the bullet shock and the blast signatures.

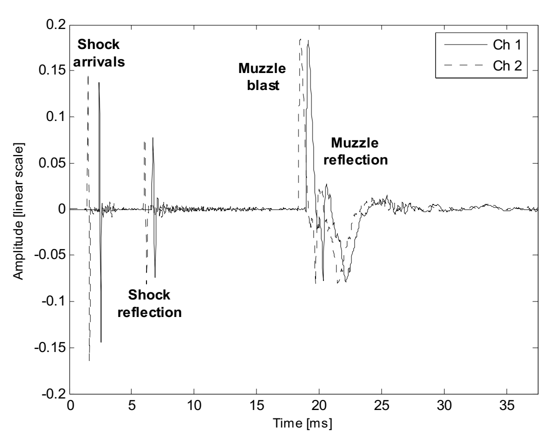

Figure 2. Two-channel gunshot recording, M=2.54, oblique trajectory toward the microphones.

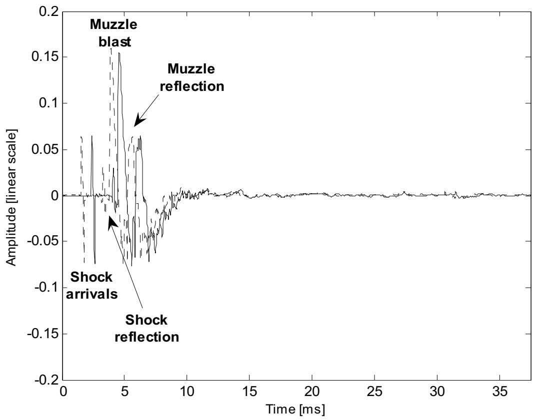

Figure 3. Two-channel gunshot recording, M=2.54, perpendicular trajectory, 8 meter offset.

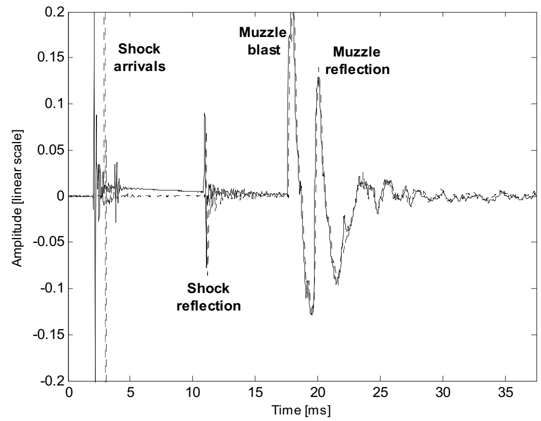

Figure 4. Two-channel gunshot recording, M=2.54, perpendicular trajectory, <1 meter offset.

The third example again uses the same ammunition and firing trajectory perpendicular to the line connecting the microphones, but unlike the second example the trajectory passes less than 1 meter from microphone 1. The resulting acoustic recording is shown in Fig. 4. The passage of the bullet very close to the microphones gives a strong initial shock wave arrival. The shock wave reflection arrives nearly simultaneously at the two microphones because the ground reflection paths for this geometry are nearly coincident. Similarly, the muzzle blast arrives nearly simultaneously at the two microphones due to the coincident acoustical paths.

The final example, Fig. 5, depicts the result when the rifle's muzzle is pointed away from the microphones. In this situation the projectile's expanding shock wave cone does not intercept the microphones. The directionality of the muzzle blast is also evident: the muzzle signature is of lesser amplitude than for the shots made with the muzzle facing the microphones.

B. *Simple Geometrical Acoustics Model*

Comparison of the measured acoustic data and a simple geometrical triangulation using known shooter position, the shock wave arrival times at the known microphone positions, and the known bullet speed and trajectory give very consistent agreement [6]. Even with microphone signals digitized at 48 kHz sample rate per channel, the 20.8 microseconds sampling interval (1/48 000) is sufficient for classification and verification purposes. However, the extremely rapid rise and fall times of the shock wave require higher sampling rates and signal bandwidths for complete characterization.

III. LOSSY PROPAGATION AND REFLECTION

This section contains a summary of several important sound propagation phenomena and environmental effects that are significant for gunshot analysis systems.

The shock wave and muzzle blast sounds, like other physical wave phenomena, are subject to reflection, attenuation, absorption, diffraction, focusing, and other wave modifications as they propagate. A microphone or other acoustic sensor placed in the vicinity of a sound source will receive acoustic pressure waves arriving directly from the source and waves arriving later from other directions due to reflections and scattering. If the presence of reflections and atmospheric propagation effects are not explicitly accounted for by the gunshot classification or sniper location system, the performance of that system must be examined carefully to assess its reliability and effectiveness in real-world conditions.

A. *Environmental Sound Considerations*

Outdoor sound propagation may vary greatly at distances of hundreds of meters from the source due to spatially varying atmospheric conditions, diffraction around obstructing objects, and reflections from the ground and other surfaces. Furthermore, acoustical propagation may be affected by wind, temperature gradients, and frequency-dependent atmospheric absorption. As the specific environmental conditions will vary greatly from one location to another, it is not possible to generate a single, comprehensive mathematical model applicable in general. Thus, empirical models are generally required to account for the environmental behavior.

Ordinary audible sounds fall within a pressure range that is well modeled with linear differential wave equations, but the

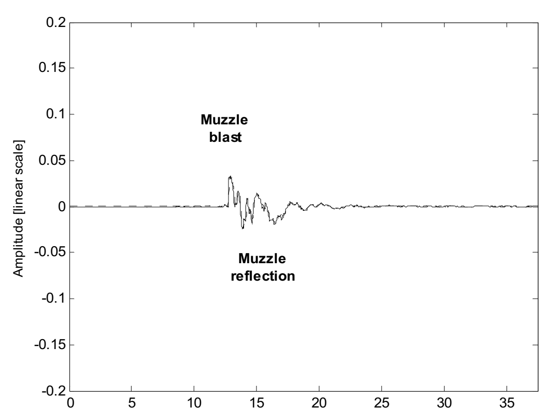

Figure 5. Two-channel gunshot recording, M=2.54, opposing trajectory (muzzle pointed away from microphones)

shock waves caused by supersonic projectiles give rise to nonlinear behavior in the air. Although it is possible to predict the acoustical properties of a particular environment using standard mathematical techniques, the absorption, attenuation, and reflection properties of objects encountered by the acoustical disturbance must be known (or accurately estimated) for both the linear and nonlinear propagation regimes.

Typical airborne sounds cover the frequency range from below 10 Hz to more than 40 kHz. Since $c = f\lambda$, the wavelengths encountered in air may range from more than 34 meters at low frequencies to less than 1 centimeter for the highest ultrasonic disturbances. This huge range of wavelengths means that diffraction and absorption properties will vary considerably depending on the spectrum of the sound source.

Temperature and relative humidity can play an important role in determining sound levels. Precipitation (rain, snow, or fog) usually does not cause a significant effect upon sound levels, although these phenomena do affect humidity, wind and temperature gradients, and generate acoustical noise due to raindrops or turbulence.

B. Effects of Wind

If the air itself is moving due to wind, the sound propagating through the air will be carried in the moving air mass. If the gun is stationary, the muzzle blast sound waves will emanate essentially spherically. The spatial motion of the muzzle blast wave front will therefore consist of the vector sum of the spherically expanding sound vector and the wind vector. Similarly, the shock wave cone formed by the supersonic projectile will be altered by the wind.

The wind effect can be viewed as a shift in the origin of the sound propagation. In other words, the wave front launched at the source is carried by the wind as it propagates toward the receiver. The propagating wave front is systematically shifted due to the wind so that by the time it arrives at the receiver position the apparent location of the sound source (or the bullet's trajectory) has been shifted as well.

Wind motion is generally accompanied by a *wind gradient*, with the wind speed typically faster at altitude and slower near the ground. The result is that sound waves propagating upwind are 'bent' upwards and those propagating downwind are 'bent' downwards.

Although wind speeds are a small fraction of the speed of sound, the wind alteration causes a direction-dependent change in sound speed, and a corresponding Doppler-like frequency shift.

C. Effects of Non-Uniform Temperature

The air temperature in the atmosphere is generally not uniform, and as indicated by Eq. (1), there will be spatial variations in the sound speed (higher speed in warmer air, lower speed in cooler air).

In the daytime, particularly in the summer months, the ground surface is often warmer than the upper air. In this situation sound propagation tends to be bent upwards slightly due to the temperature gradient: the wave front in the warm air near the surface propagates faster than the wave front in cooler air higher above the ground. Conversely, in winter or at night when the temperature near the ground is likely to be lower than that of the upper air, sound waves tend to be bent downwards.

The combined effects of wind and temperature gradients can cause sound levels measured some distance from the source to be very different from predictions based on geometrical spreading and atmospheric absorption considerations alone. These differences may be 20 dB or more over distances of a few hundred meters.

D. Ground Surface and Obstacles

Gunshot sounds propagating over ground will encounter attenuation by acoustic energy losses due to scattering. Smooth and hard ground will generally produce less absorption than rough surfaces such as vegetation. Higher frequencies (shorter wavelengths) are almost always attenuated more than lower frequencies. Measurements in forested areas show that absorption and scattering can achieve significant attenuation. There can also be significant attenuation by acoustic shadowing when a solid obstacle obscures the 'line of sight' between the source and the acoustic sensor.

E. Humidity Effects

The relative humidity of the air causes frequency-dependent sound absorption due to molecular thermal relaxation. The attenuation is found to increase monotonically with increasing frequency, and is the greatest for relative humidity in the 10-30% range. Below 4 kHz, the worst-case humidity attenuation corresponds to 0.1dB/m [7].

In summary, the importance of these atmospheric factors depends on the situation under consideration. For example, for a sound source near the ground and within 25 meters of the acoustic sensor, geometrical spreading of the propagating wave front may be the only significant consideration. If the sensor is a much greater distance from the source, such as 100 meters or more, then the surface conditions, obstacles, and atmospheric effects must also be considered.

IV. Other Practical Considerations

A subsonic rifle or handgun without a suppressor will produce a muzzle blast acoustic signal, but the subsonic projectile will not create a shock wave or any other appreciable acoustic signal as it propagates through the air. A recording of a handgun and subsonic bullet (HK USP compact, 40 Smith and Wesson, Federal Hydroshock) is shown in Fig. 6. Note that no shock wave signature is present. The muzzle blast of this particular handgun is less intense and shorter in duration than the muzzle blast of the rifle shown in Figs. 2-4.

It would be desirable for criminal forensic analysis to be able to identify a specific firearm from an audio surveillance recording, such as a 911 call or a tape of a land mobile radio conversation in which a gunshot was captured, but

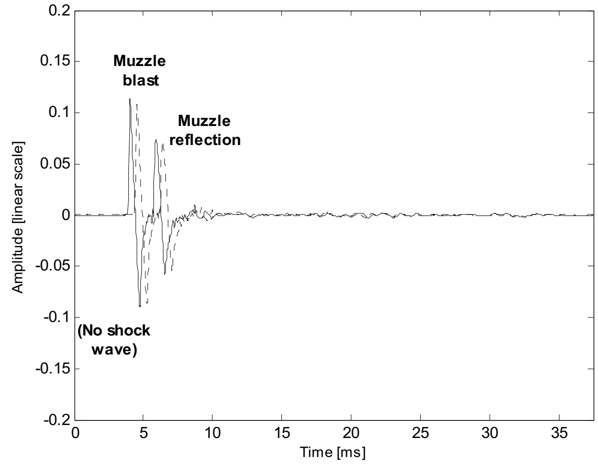

Figure 6. Two-channel gunshot recording, subsonic projectile (muzzle blast and reflection only, no shock wave)

conventional audio recordings have not been shown to be reliable for identifying particular firearms [1]. However, recordings obtained in a controlled manner such that the orientation of the firearm and the distance between the gun and the microphone are held constant do show consistency from one shot to another [2].

At distances far from the bullet's trajectory, the shock wave will have expanded sufficiently by spatial spreading that it may no longer be detectable compared to ambient noise. Also, as noted previously, the situation is much more complicated if the acoustical surroundings include obstacles and reflecting surfaces so that the received acoustical signal contains multi-path interference, diffraction effects, and other propagation-related flaws. The very short duration of the muzzle blast and the acoustic shock waves act like acoustic impulses, so gunshot recordings obtained in complicated surroundings will consist of the convolution of the gun's report and the acoustic impulse response of the local reverberant environment, resulting in substantial temporal smearing. In fact, reverberant recordings will typically contain more information about the acoustical surroundings than about the gun or the projectile. Deconvolution of the gunshot from the reverberant background can be attempted, but no completely reliable means to accomplish this task for gunshots has been published.

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