DECIPHERING GUNSHOT RECORDINGS

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Audio gunshot recordings can be helpful for crime scene reconstruction, estimation of the shooter's location and orientation, and verification of eyewitness accounts. The audio evidence can include the muzzle blast, the shock wave signature if the projectile is traveling at supersonic speed, and possibly even the characteristic sound of the firearm's mechanical action if the recording is obtained close to the shooting position. To investigate the acoustical phenomena associated with gunshot evidence, a systematic set of rifle shots were made from distances ranging from 10 meters to nearly 800 meters away from the recording microphone. This paper summarizes the primary acoustical evidence derived from these recorded gunshots, and suggests several strengths and weaknesses of gunshot analysis for forensic purposes.

INTRODUCTION

The seemingly unmistakable sound of a gunshot presents an interesting challenge for forensic acoustical analysis. The extremely fast rise times associated with acoustical shock waves, the unusually high sound pressure levels caused by the muzzle blast, and the very short duration of the direct sonic signatures all present a challenge to conventional audio recording gear [1-3].

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 conventional audio recordings have not been shown to be reliable for identifying particular firearms [4]. 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 [5]. Recordings with an unobstructed direct sound path from the firearm to the microphone often provide excellent time-of-arrival agreement with predictions from geometrical acoustics [1].

This paper reports the results of a systematic sequence of gunshot audio recordings obtained under controlled conditions. We conducted several experiments using a .308 Winchester rifle fired horizontally in the direction of a target located a known distance away while we obtained audio recordings of the gunshot acoustical signals at several distances from the firearm. Our interest was to determine the characteristic behavior of gunshot acoustic signals under known conditions to help inform forensic gunshot signal analysis and to predict propagation distance and audibility in the presence of ambient noise.

The remainder of this paper is organized as follows. First, the basic principles of firearm acoustics relevant to audio forensics are reviewed, with emphasis on rifles and supersonic projectiles rather than handguns. Next, the behavior of the sound field close to the rifle shooting position is considered, followed by similar characteristics for the sound field close to the target. The paper concludes with several suggestions and cautions regarding gunshot recordings.

1 FIREARM ACOUSTICS

A conventional firearm uses a confined combustion of gunpowder to propel the bullet out of the gun barrel. The explosive gases expand rapidly behind the bullet, abruptly forcing a supersonic jet of gas from the muzzle. The muzzle blast causes an acoustic shock wave and a brief, chaotic explosive sound lasting only a few milliseconds. The peak sound pressure level associated with the muzzle blast can exceed 150dB in the vicinity of the firearm. The muzzle blast is often highly directional: the on-axis level is generally more intense than the level toward the rear or to the side.

Once the gunpowder combustion is complete, the firearm itself may produce much more subtle mechanical sounds, such as post-shot motion of the trigger and cocking mechanism, ejection of the spent cartridge, and positioning of new ammunition. These characteristic sounds may be of interest for forensic study if the microphone is located sufficiently close to the firearm to pick up the tell-tale sonic information.

Besides the muzzle blast and sound of the firearm's mechanical action, the only other potential sources of forensic audio material are the passage of the bullet through the air and the sound of the bullet striking its target. Bullets travelling at subsonic speed are designed for aerodynamic efficiency and generally do not create noteworthy acoustical effects as they travel down range. However, bullets shot from a firearm with supersonic velocity inherently cause the formation of an acoustic shock wave propagating outward away from the bullet's path like a cone trailing the projectile [1-3].

1.1 Supersonic projectile

The shock wave front itself propagates at the speed of sound. The shock wave geometry depends upon the ratio of the projectile's speed, V, to the local speed of sound, c. The ratio $M = V/c$ is known as the *Mach Number* of the moving object. Thus, a projectile traveling faster than the speed of sound has $M>1$, while a subsonic projectile will have a fractional Mach Number ($0<M<1$).

Specifically for supersonic projectiles ($M>1$), the angle between the bullet path and the resulting shock wave is given by

$$\theta_M = \arcsin\left(\frac{1}{M}\right), \qquad (1)$$

where θ_M is referred to as the *Mach Angle* [1]. The Mach Angle ranges from nearly 90° if the bullet is barely supersonic, to a narrow angle of 30° or less for high-velocity projectiles, as shown in Figure 1.

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

$$c = c_0\sqrt{1+\frac{T}{273}}, \qquad (2)$$

where T is the air temperature in degrees Celsius and c_0 = 331 m/s is the speed of sound at 0° C. Note that the temperature dependence of c implies a change in the ratio M, and therefore temperature needs to be accounted for when determining the expected Mach Angle for a given projectile speed. For example, a projectile traveling at 800 m/s has Mach Number 2.42 at 0° C, or 2.33 (3.7% lower) at room temperature (20° C).

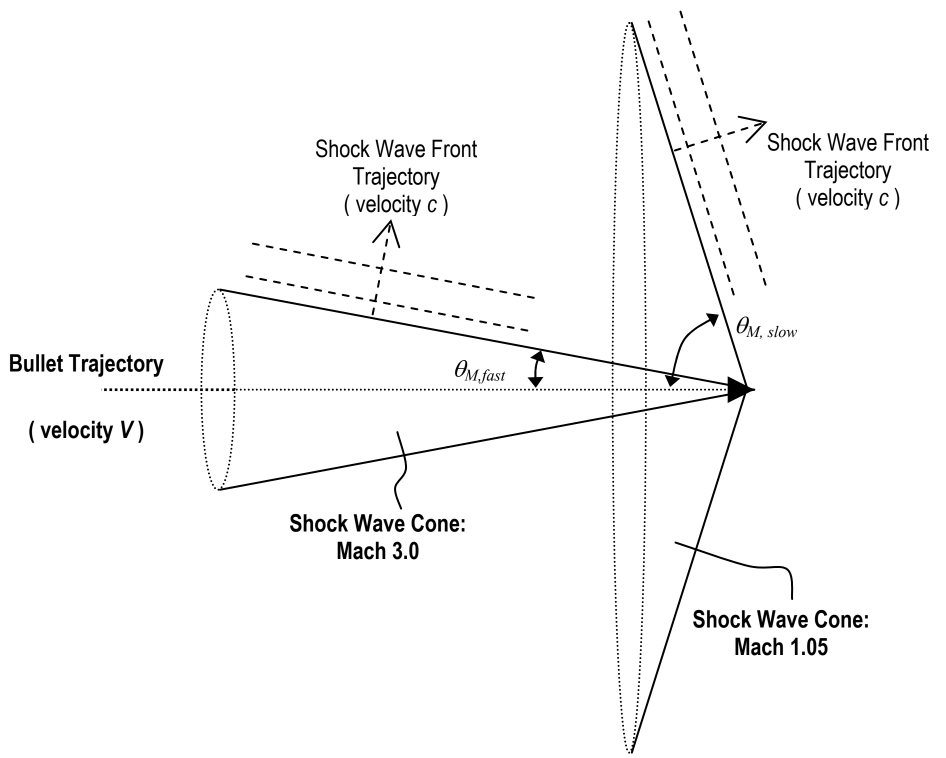

Figure 1: Shock wave geometry for a supersonic Mach 3 projectile and a slower supersonic Mach 1.05 projectile.

The bullet traveling faster than the speed of sound outpaces the propagating shock wave and the muzzle blast wave fronts which move at the speed of sound. This means that a microphone located down range from the shooting position will typically receive the shock wave arrival considerably before the arrival of the muzzle blast.

For supersonic projectiles, a set of microphones placed at known locations within the path of the shock wave can provide an estimate the shock's propagation direction. Note, however, that determining the bullet's trajectory from the shock propagation vector requires knowledge of the bullet velocity, V, or sufficient spatial information to deduce the Mach angle. Two bullets following the same path but at different speeds may create substantially differing shock wave propagation directions, as was shown in Figure 1. In other words, if V is not known, then the shock wave cone angle is also not known, and the bullet's trajectory cannot be determined exactly without additional spatial information. This physical reality is important to consider when examining gunshot acoustic evidence.

1.2 Reflections and reverberation

The practical forensic audio situation is likely to be much more complex because the acoustical surroundings will include obstacles and reflecting surfaces creating multi-path interference, diffraction effects, and other acoustical propagation-related detail 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 environment, resulting in substantial temporal smearing and clutter. Using deconvolution techniques to extract the shot detail from the multi-path clutter is an appealing concept, but little has been published regarding techniques that are generally applicable for forensic interpretation.

The booming gunshot sounds used in motion picture and television sound effects libraries are actually dominated by the reflections and reverberant echoes after the shot rather than the direct impulsive gunshot sound itself. Unless the direct sound of the shot can be isolated prior to the arrival of reflections, reverberant recordings will typically reveal more about the acoustical surroundings of the recording scene (i.e., the acoustic impulse response) rather than the characteristics of a particular firearm. Reverberant gunshot recordings have artistic and emotional value for the cinema, of course, but may be difficult to parse for forensic purposes.

2 ACOUSTICS NEAR THE FIREARM

The gunshot sound field near the firearm presents two specific challenges for audio forensics. First, the sound level of the muzzle blast—and the shockwave if the bullet is supersonic—are well in excess of the normal audio recording range and this almost always leads to amplitude clipping in the recording itself. Second, the proximity of the microphone to the firearm leads to relatively short time gaps between the muzzle blast, ballistic shock wave, and the arrival of the corresponding reflections from the ground and other nearby objects, possibly making it difficult to resolve the sonic details.

Gunshot recordings obtained from mobile telephones, electronic news gathering rigs, and even high quality professional recording systems are subject to amplitude clipping by the microphone, preamplifier, and other elements in the recording chain, and therefore often cannot reveal useful detail about the shot or shots captured in the recording. Many contemporary sources of audio recordings may include a processing chain containing perceptual audio coding algorithms (e.g., MP3 or a mobile telephone codec), which are designed to maintain perceived sound quality or speech intelligibility, not precise information about atypical sounds such as gunshots. Despite clipping and the probable waveform distortion if an audio coding algorithm is present, it is often still possible to determine useful temporal information from the recording if the sampling rate is sufficiently high and the audio coding algorithm handles time-scale information in a known, linear fashion. Forensic examination of such recordings must be done with care.

2.1 Gunshot demonstration 1

Figure 2 shows an example firearm recording obtained

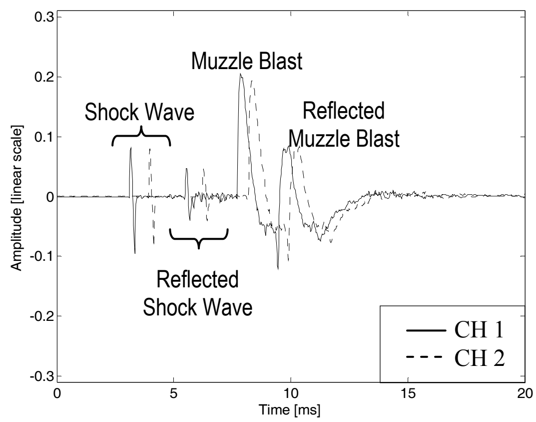

Figure 2: Gunshot recording #1, M=2.54, (geometry shown in Fig.3)

under carefully controlled conditions to avoid clipping. The firearm used was a rifle chambered for .308 Winchester cartridges. 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 2.54, giving a Mach cone angle (θ_M) of 23.2°. A two-channel recording was obtained using a matched pair of professional omnidirectional electret condenser microphones (DPA 4003), a corresponding high voltage preamplifier (HMA 5000), and stereo audio recorder operating with 16-bit resolution and a 48 kHz sample rate per channel. For this recording the microphones were spaced 30cm apart and mounted 1.6m above the sandy, frozen surface of a firing range. The gunshot was directed parallel with the ground surface in a trajectory that would pass perpendicular to an imaginary line connecting the two microphones, at a distance of approximately 9 meters from the closer of the two microphones. This geometry is depicted in Figure 3.

There are several important and significant details evident in the gunshot recordings of Figure 2. The first important observation is that the duration of the near field gunshot sonic events are of very brief duration indeed. The shock wave front lasts less than 300 microseconds and the muzzle blast lingers for less than 5 milliseconds. The 48 kHz sample rate is not sufficient to resolve the shock wave details. The overall duration from shock wave arrival to passage of the muzzle blast in this example, including the first-order reflections from the ground surface, lasts just 10 milliseconds. A second important observation is that even in this very simple acoustical environment involving only the ground surface, the ground reflections are of nearly equal acoustic level and significance to the direct gunshot sound itself. In fact, the muzzle blast reflection arrives at the microphone before the direct sound has subsided, thereby creating an overlapping signature. The third important observation is that the relative timing of each sonic component is largely governed by the geometric relationship between the firearm and the microphone, and therefore we may be able to deduce useful forensic information from the recording about the gunshot scene [1, 2]. This topic is considered in more detail next.

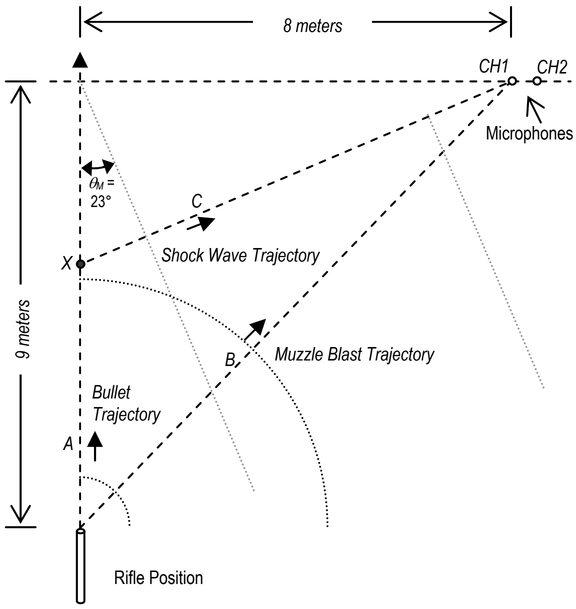

Figure 3: Geometry of the example gunshot recording from Figure 2.

The shooting range geometry shown in Figure 3 consists of the rifle (lower left) and the microphones (upper right). In this particular test, the rifle bullet leaves the muzzle traveling at Mach 2.54 and proceeds along path A. At the same time, the expanding gas leaving the muzzle produces the muzzle blast sound, which expands outward at the speed of sound. The shortest distance from the muzzle to the microphones is along the straight path labeled B, which is approximately 12 meters in this case. Thus, the muzzle blast will take roughly $12/c = 12/328 = 36.7$ ms to reach the microphones.

The muzzle blast sound will also reflect off surrounding surfaces (primarily the ground in this case) and reach the microphones later due to the longer path traversed by the reflection.

The shock wave caused by the passage of the supersonic bullet expands outward behind the bullet at the speed of sound, but in the direction determined from the Mach Angle. The shock wave front ray's arrival at the microphones will follow path C, which corresponds to the shock wave produced when the bullet was at location X. The resulting geometric calculation places X at 5.57 meters from the muzzle, path C is 8.70 meters, and the overall time between the shot and the shock wave arrival is the sum of the time required for the bullet to travel from the muzzle to point X, and the time required for the shock wave to travel at the speed of sound from point X to the microphones: $5.57/2728 + 8.7/328 = 28.6$ ms. The differing propagation times result in approximately 8 ms delay between the shock wave arrival and the direct arrival of the muzzle blast.

The ground reflection of the shock wave ray will propagate at the same azimuth as path C, but along the longer path from the muzzle down to the ground and back up to the microphones. The longer path traversed by the shock wave reflection results in its arrival being delayed by a proportional amount.

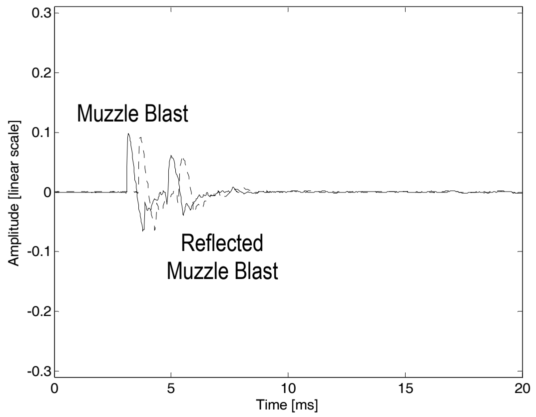

Figure 4: Two-channel gunshot recording #2,
M<1 (subsonic)
(geometry shown in Fig.3)

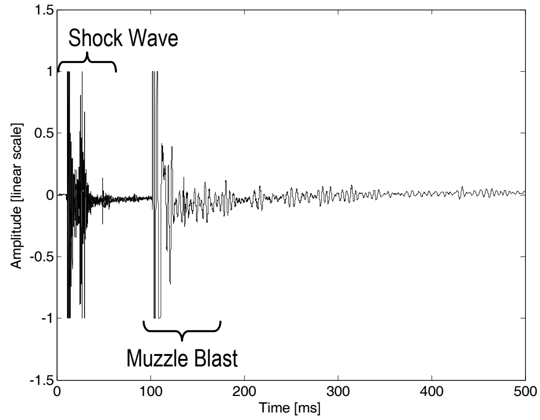

Figure 5: Gunshot rifle recording #3,
60 meters downrange

2.2 Gunshot demonstration 2

An additional near field demonstration recording is shown in Figure 4. This recording was obtained using the same geometry as shown in Figure 3, but with a hand gun and a subsonic projectile. Note that the recording reveals the muzzle blast arrival and the overlapping arrival of the muzzle blast ground reflection, but no shock wave because the bullet speed was less than the speed of sound.

In summary, the gunshot sound field near the shooting position is generally quite well defined for the arrival of the direct sound of the muzzle blast and the ballistic shock wave if the projectile is supersonic. The timing and behavior of these initial sonic events are well predicted by geometrical acoustics. However, once the sound field includes first and higher-order reflections and reverberation, the sonic signature is less easily deciphered due to its dependence upon the acoustical surroundings that are typically independent of the firearm itself.

3 ACOUSTICS NEAR THE TARGET

The gunshot recordings presented in Section 2 were obtained within a few meters of the firearm and with only the first-order ground reflection in addition to the direct sound of the shot. If the acoustic information is obtained downrange at the target location, the range effects and bullet trajectory become more significant.

To investigate the acoustical propagation effects at greater distances, we placed two omnidirectional microphones (DPA 4006-TL, phantom powered) adjacent to the target and arranged a stereo digital audio recorder to capture the signals with 24-bit resolution and a 48 kHz sample rate per channel. Multiple rifle shots were made with a .308 Winchester from distances of 66, 100, 385, 600, and 800 yards (60, 91, 352, 549, 732 meters, respectively). The muzzle velocity for the particular ammunition used was 2728 ft/sec (831.5 m/sec) and the speed of sound was 1083 ft/sec (330 m/sec) at approximately 30°F (-1°C). For this particular rifle and ammunition the projectile was traveling at supersonic speed throughout the distance from the muzzle to the target, but deceleration of the bullet is an important consideration, as described in section 3.3 below.

3.1 Gunshot behavior down range: demonstration 3

A demonstration recording for 60 meters (66 yards) downrange is shown in Figure 5. The rifle marksman was shooting from a prone position on the ground toward the target that was mounted approximately one meter above the ground surface. The shot trajectory passed 5 meters from the microphone position. Note that this recording has been clipped in amplitude (unity represents the clipping level).

This example recording from a down range position reveals a much more complicated sonic pattern than was evident in the relatively pristine recordings from the shooting position. In particular, the reflections and corresponding delayed sound arrivals caused by passage over the uneven ground surface lead to much more intricate pressure disturbances and characteristics that depend less upon the firearm and more upon the acoustical properties of the firing range. Moreover, the shock wave caused by a supersonic projectile may become distorted due to the non-linear propagation and dispersion behavior of acoustic shocks, and the general dissipation of acoustic energy due to spreading of the expanding shock wave front [3].

3.2 Gunshot demonstrations 4-7

As the distance down range increases, the spherical energy spreading of the muzzle blast reduce its level in comparison to the shock wave projected by the supersonic bullet.

The relative arrival times of the bullet's shock wave and the muzzle blast from the gun barrel can be predicted by geometric acoustics. The shock wave Mach cone trailing the bullet is projected downrange as the projectile travels, while the muzzle blast disturbance propagates behind at the speed of sound. With the microphone located 5 meters off-axis, the supersonic bullet travels a substantial distance past the microphone position before the shock wave cone actually reaches the microphone.

Figures 6-9 show acoustic demonstration recordings 4 through 7 obtained near the target position located 91, 352, 549, and 732 meters, respectively, from the firing position. Note that the horizontal axis time range increases with each plot.

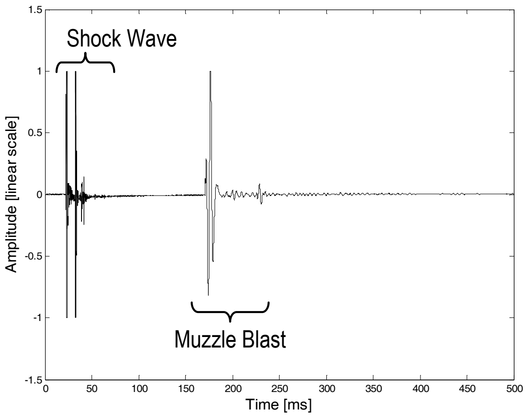

Figure 6: Gunshot rifle recording #4, 91 meters downrange

3.3 Acoustical effects of bullet deceleration

The ballistic characteristics of a bullet depend on the size, shape, and mass of the projectile, and the temperature, pressure, and wind in the atmosphere. The aerodynamic drag encountered by the bullet also varies as a function of the bullet's speed. The complexity and nonlinearity of the ballistic dynamics are typically addressed by empirical testing [6].

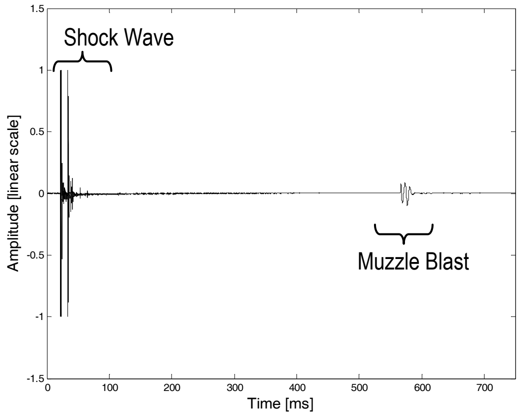

Figure 7: Gunshot rifle recording #5, 352 meters downrange

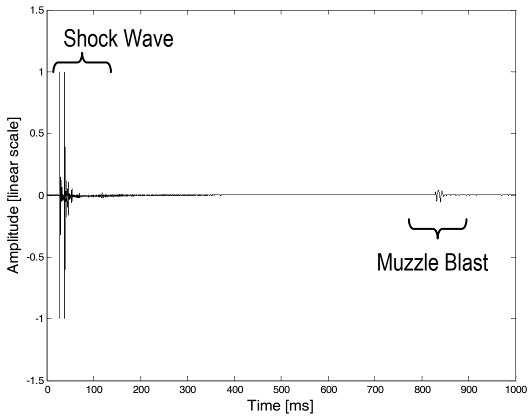

Figure 8: Gunshot rifle recording #6, 549 meters downrange

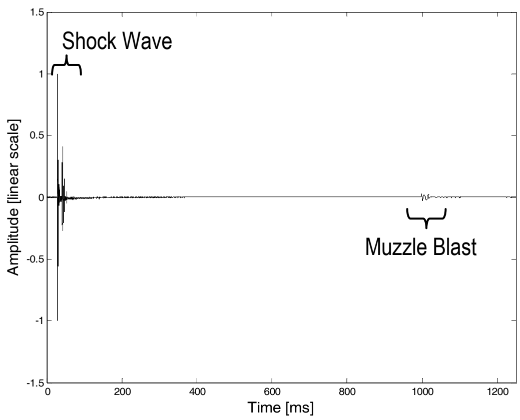

Figure 9: Gunshot rifle recording #7, 732 meters downrange

For a supersonic projectile, the deceleration of the bullet as it travels toward the target causes the Mach cone trailing the bullet to broaden steadily before finally reaching 90° and then disappearing as the projectile drops below the speed of sound.

Even as the supersonic bullet slows, the muzzle blast sound continues its propagation at the speed of sound from the barrel to the downrange position. Thus, the relative time of arrival of the shock wave and the muzzle blast depends on the geometric orientation of the shot trajectory and the deceleration profile of the bullet. Forensic predictions of shooting location based on acoustic recordings downrange must take into account these important acoustical variables.

An example deceleration and Mach Angle chart as a function of distance downrange is shown in Figure 10 for the .308 Winchester ammunition used in rifle demonstrations 3-7. In this example c = 330 m/s and V_{muzzle} = 803 m/s so the projectile remains supersonic over the entire 700 meter distance, but note that the bullet slows to only half its muzzle velocity as it travels that distance through the air.

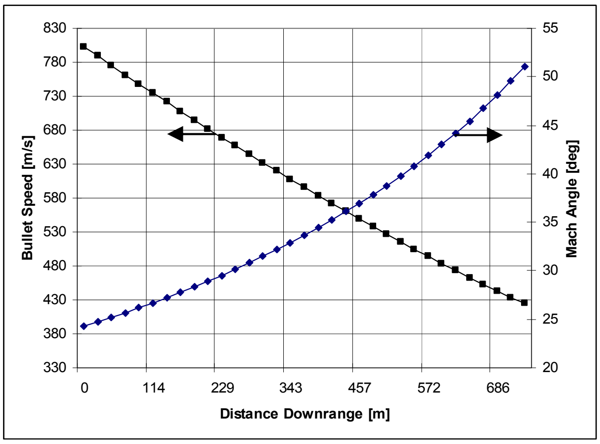

Figure 10: Example bullet deceleration and shock wave Mach Angle as a function of distance down range

The downrange effect of the deceleration broadens the effective shape of the shock wave cone contour, resulting in a range-dependent shock wave propagation vector [3]. This effect is shown in Figure 11 as a set of curves denoting the shock wave position and shape as a function of time. Specifically, the portion of the shock wave that is launched early in the flight when the bullet is traveling the fastest propagates with a steeper cross range vector than when the bullet slows down range.

4 CONCLUSION

This paper is intended to explain several important acoustical phenomena related to gunshot recordings that

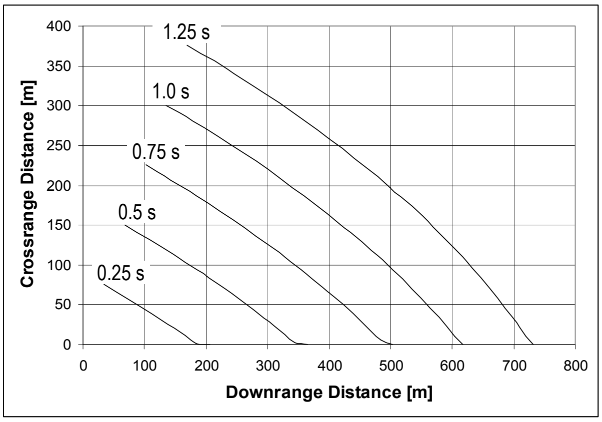

Figure 11: Shock wave profile versus time as a function of distance down range

are the subject of forensic interpretation. It is important to note that the example recordings in this paper were obtained with professional recording microphones under very quiet background conditions in very simple acoustical environments, i.e., with essentially no nearby reflecting surfaces except for the ground.

Forensic recordings obtained with less reliable microphones in complicated acoustical surroundings will undoubtedly contain information that is problematic for valid, confident interpretation. The high sound levels associated with gunshots will generally overload the microphone and its associated electronics, causing signal distortion and ringing in the recorded signal that may be difficult to separate from the acoustic evidence itself. Situations in which the recording microphone has an acoustically obstructed view of the firearm or the bullet's shock wave (for supersonic projectiles) can also be difficult to explain from the simple geometrical arguments used in this paper.

Therefore, the forensic audio examiner is advised to obtain meaningful and corroborating experimental support before drawing conclusions from recorded gunshot evidence.

5 ACKNOWLEDGEMENTS

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