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The Acoustics of Gunfire

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ABSTRACT

Gunfire results in acoustic emission of 1) an impulsive muzzle blast report from weapons without sound suppression, and 2) a traveling shock wave (i.e., N-wave) from the supersonic projectile discharged from most center fire rifles. Classic theory and International Organization for Standardization (ISO) standards for predicting these emissions are reviewed and compared with empirical data. The measurement of high level and very short-duration N-waves is discussed. Spectral measurement data is presented. The acoustic effects of sound suppression systems, muzzle brakes and compensators are reviewed. Gunshot forensic issues are outlined, and audibility and weapon identification by gunshot signature are discussed. Application of muzzle blast and N-wave prediction are discussed for a sniper location detection system.

1 INTRODUCTION

Gunfire acoustics are of interest to technical professionals in providing the basis of understanding for a wide range of acoustic emissions, and to criminal investigators examining gunshot recordings to determine the events at a crime scene. This paper is subsequently presented in two parts: explanation of the mechanisms for gunfire prediction and propagation, and case studies and applications of gunshot acoustic technology. An understanding of the physics and acoustics of gunfire can aid the forensic examiner in assessing audibility and discriminability.

1.1 Background

A firearm can be characterized as a heat engine that converts stored chemical energy into kinetic energy. This is achieved by igniting propellant within a cartridge to produce short-duration high pressure in a chamber that discharges a projectile at a high velocity. To analyze the acoustic emissions of gunfire we will review the events of a rifle discharge; pistols and shotgun discharges emissions may also be generally understood from this example.

When the trigger of a firearm is pulled, it actuates a mechanism enabling a spring-loaded firing pin to strike and ignite a small ignition cap (the primer) centered in the base of a cartridge (for center-fire ammunition). This ignites the cartridge propellant, which does not explode but burns rapidly and progressively (with an accelerating burn rate). This creates a high pressure within the cartridge forcing the bullet (the projectile) to release its compression fit from the cartridge and accelerate down the barrel and out the muzzle. The entire event takes place in 1.0 – 1.6 msec, with peak internal breech pressures of 240 – 450 MPa (35,000 – 65,000 psi) and a

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typical peak temperature of 3,065 °C (5,550 °F) discharging the bullet at a muzzle velocity of 760 - 1220 m/sec (2,500 – 4,000 ft/sec). Most barrels also include 'rifling' which causes the bullet to spin as it travels. The bullet is typically spin-stabilized at 150,000 – 360,000 rpm.[1] As the bullet travels down the barrel the increasing volume of the pressure chamber causes a rapid reduction in pressure behind the bullet to around 40 MPa (6,000 psi) at muzzle discharge.

The total chemical energy of a rifle discharge is 4,000 – 12,000 Joules (3.8 – 11.4 Btu). The resulting kinetic energy of the bullets at discharge is 1350 – 4050 Nm (1,000 – 3,000 ft-lbs).[2] However, firearms are an inefficient heat engine, since only 30 - 40 percent of the chemical energy is transferred to the projectile. About 20 – 30 percent is transferred to the barrel as heat, 25 percent to escaping gas, 10 percent to recoil, 3 percent to friction, 2 percent in unburned propellant, and less than 1 percent as acoustic energy.

2 MUZZLE BLAST

2.1 Classical Model

Muzzle blast, or firearm report, is the most dominant noise source and is produced by all gunshots unless a sound suppressor (i.e., silencer) is employed. In the far field, a muzzle can be described as a noise generating tube similar to a simple acoustic monopole source.[3] This is often modeled as an uncorked pressure cylinder whereby the sound diverges as a symmetrical sphere. Such a monopole source may be envisioned as a spherical balloon uniformly expanding or contracting, generating sound pressures that diverge uniformly. The far field sound pressure for such a source is given by: [4]

$$p = \frac{\rho_0}{4\pi r}\left(\frac{d^2 Q}{dt^2}\right) \tag{1}$$

where

- p = far field sound pressure
- ρ_0 = ambient air density;
- r = distance from source;
- Q = volume of ambient air being displaced by the source;
- t = time.

For the typical condition of isentropic expansion and supersonic discharge where the flow velocity equals the local sonic velocity,

$$P = P_t\left(\frac{A_t}{4\pi x^2}\right)^{\frac{2\gamma}{\gamma+1}} \tag{2}$$

where

- P_t = absolute pressure of gas at discharge;
- A_t = source gas discharge area;
- x = distance from center of source;

γ = gas ratio of specific heats.

2.2 ISO Model

The classical model predicts peak sound power of muzzle blasts to be 140 dB - 180 dB. This generally agrees with empirical data. However, muzzle blast is directional with sound levels on-axis ahead of the muzzle higher than levels directly behind the muzzle by up to 20 dB. Thus, the omni-directional monopole model does not conform directionally to the empirical data. Figure 1 shows the measured radiation pattern of a muzzle blast, reported in an ISO standard.[5]

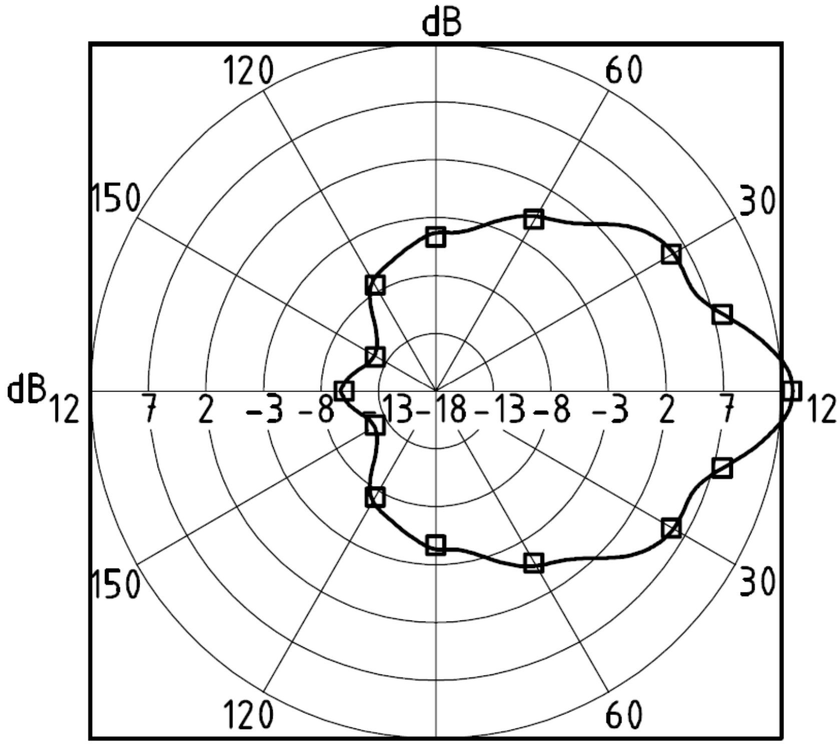

Figure 1: ISO 17201-1 measured radiation pattern.

It is clear from the measured muzzle blast radiation patterns in Figure 1 that the basic monopole model does not account for the directivity of muzzle blasts. Directivity is addressed in the ISO standard that is based upon the chemical energy of the cartridge. The ISO prediction of muzzle blast sound is a complex procedure, which incorporates empirical methods with the theory. The ISO model assumes that the acoustic energy is proportional to the total chemical energy of the discharge, but acknowledges a variation in acoustical efficiency. The equation for the angular source energy distribution [$S_q(\alpha)$], giving both magnitude and direction, is giving in the ISO standard:[6]

$$S_q(\alpha) = \frac{p^2 w}{pc} 4\pi R_w^2 \int_{\omega_1}^{\omega_2} \frac{1}{\pi}\left[\omega^2 + 9\frac{c^2}{R_w^2}\left(\frac{c^2}{R_w^2\omega^2} + 1\right)\right]^{-1} d\omega \tag{3}$$

where: $$R_w = \sqrt[3]{\frac{Q_y}{Q_w}}$$

Q_y is directional energy and Q_w is the total energy within the 'Weber radius'

R_w is the Weber radius, or the radius of an equivalent radiating sphere of the "simple model of explosion"

p, c, ω and ρ are pressure, speed of sound, angular frequency and air density, respectively

Unfortunately, the chemical energy of the cartridge and the thermal/kinetic efficiency are not well documented, thereby requiring estimation of these critical parameters, such as the percent of chemical energy transferred to acoustic energy (0.25 percent). Therefore, no universal prediction procedure is widely accepted for the prediction of muzzle blast noise. The sound power level values for most firearms seem to fall within a relatively small range. The spectrum of the muzzle blast also seems to be somewhat consistent and the ISO standard spectrum is shown in Figure 2.[6]

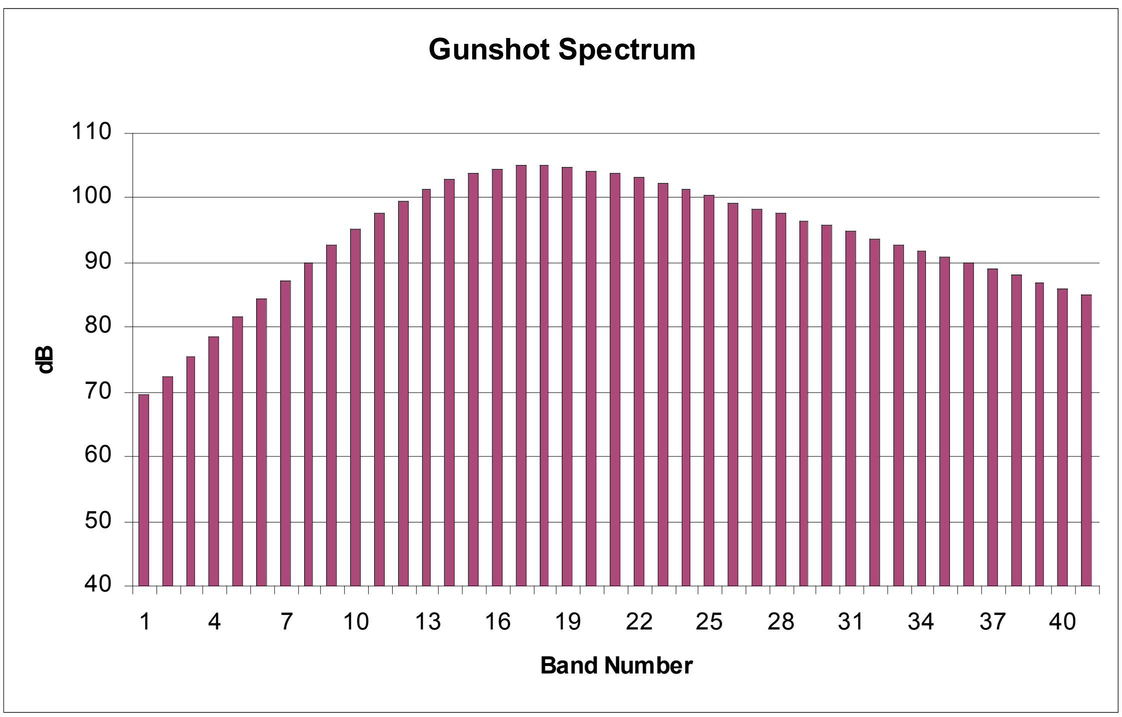

Figure 2: ISO Standard Spectrum for Muzzle Blast

2.3 Directivity

One explanation for the directivity of muzzle blasts is that the sound source is rapidly accelerating at muzzle discharge. Here the report behaves as a monopole, but one that is accelerating around 900 m/sec (3,000 fps). The spherical pressure wave from the discharge expands very rapidly, decreasing exponentially with time. But, the time period is very short at this high velocity, and the result is a somewhat elliptical radiation pattern such as that shown in Figure 1.

2.4 Muzzle Blast Mitigation

The initial acoustic emission from gunfire is the muzzle blast. Some rifles employ muzzle brakes, and/or vents located at the muzzle to reduce recoil. Muzzle brakes change the directivity of the muzzle blast and attendant sound pressure wave producing lower levels forwarding front of the firearm. Some pistols use compensators (usually those employed by high power or competition shooters), which are similar devices to reduce recoil. Firearm sound suppressors are similar in design to other silencers used to reduce sound emissions from high velocity air or gas release such as from internal combustion engines or gas valves. These devices reduce sound emission by relaxing the abrupt pressure release to the atmosphere and provide for more gradual expansion to the surrounding atmospheric pressure. Control valves in pipelines use similar techniques to reduce acoustic emissions.

There are many sources of measured data for the muzzle blast of various firearms as well as draft international standards for conducting and reporting sound emission tests from muzzle blasts. Whatever subtle effects the small differences in bullet caliber may have upon the acoustic signature, they do not generally allow for weapon or caliber identification. The rise time of muzzle blasts recorded near the source is usually only a few microseconds, making it impossible to record with consumer-grade microphones and recorders. It is generally not possible to identify a particular weapon or caliber from a recording made with consumer grade equipment.

3 SHOCK WAVE

The second acoustic emission is a shock wave that is only associated with any supersonic projectile. Generally, pistol bullets either leave the muzzle subsonically or are relegated subsonic soon after. Nearly all rifle bullets depart the muzzle supersonically (except small caliber rimfire bullets) but are rapidly slowed by air friction along their trajectory. Table 1 reviews some ballistic characteristics of two popular cartridges, the 0.308 caliber and the .223 Remington[7] caliber.

Table 1: Ballistic characteristics of two cartridges:

		At muzzle			**At 457 m (500 yds)**		
Rifle Caliber	**Bullet Wt (grains)**	**Velocity mps (fps)**	**Mach Number**	**Mach Angle**	**Velocity mps (fps)**	**Mach Number**	**Mach Angle**
0.223	55 gr	988(3240)	M=2.98	20º	387(1270)	M=1.17	59º
0.308	150 gr	860(2820)	M=2.60	23º	475(1560)	M=1.44	44º

The projectile creates a moving shock wave as it progresses along the trajectory. The faster the bullet, the more streamlined the traveling shock wave. The angle of the shock wave with respect to the trajectory is called the Mach angle and can be calculated from the following formula:[8]

$$\Phi = \sin^{-1}\left(\frac{1}{M}\right) = \sin^{-1}\left(\frac{c}{v}\right) \tag{4}$$

The traveling shock wave does not propagate at a constant angle, but rather diverges to a wider angle as the bullet slows along its trajectory, and terminates at 90 degrees when the bullet reaches the speed of sound, Mach 1. Once the shock wave is propagated from a point along the trajectory it travels at Mach 1. It is therefore a straightforward matter to compute the time between the shock wave and the muzzle blast at any point downrange of the firearm discharge.

The shock wave propagated from the supersonic projectile is a classic N-wave with a characteristic time signature of a vertical rise in positive pressure, linear decline in pressure to a negative value, and vertical recovery to atmospheric pressure. Figure 3 shows a classic N-wave for a supersonic projectile.

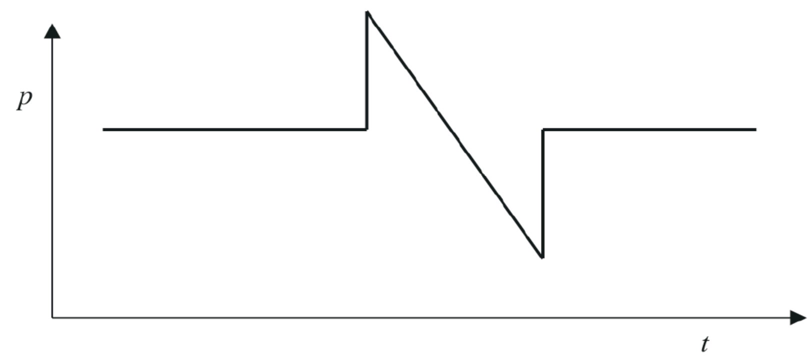

Figure 3: Assumed N-shaped waveform for the sound of a supersonic projectile 1 m from a source point on the projectile's trajectory.

This is the same sonic boom that an aircraft creates as it travels faster than the speed of sound. The length of the N-wave is related to the length of the projectile, so aircraft produce a much longer N-wave and attendant lower frequency boom than do bullets. Following are the basic parameters of the N-wave:

$$\frac{\Delta P}{P_0} = 0.53d\,\frac{\left(M^2-1\right)^{1/8}}{x^{3/4}l^{1/4}} \quad \text{and} \tag{5}$$

$$L = 1.82d\,\frac{Mx^{1/4}}{\left(M^2-1\right)^{3/8}l^{1/4}} \approx 1.82d\left(\frac{Mx}{l}\right)^{1/4} \tag{6}$$

where d and l are the projectile (bullet) diameter and length, and

L is the length of the N-wave; $L = cT$

As the N-wave propagates the short rise and fall times relax and the N-wave begins to approximate an S-wave. It is fairly easy to detect but difficult to measure the extremely short rise and fall times of the shock wave close to the source. The peak sound pressure levels often exceed 150 dB and the projectile length makes the duration of the N-wave less than 200 μsec.

4 CASE STUDIES

4.1 Gunshot Audibility/Detection

An issue often arising in forensic audio work is the question of gunshot audibility. Many cases have been concerned with the ability of a listener, with normal hearing, to detect gunshots, to discriminate gunshots from other types of impulsive sounds, and to even identify the type of weapon. Either "ear witness" reports or recordings on tapes are typically analyzed.

Gunshot audibility and discrimination is complex. The principal factors determining audibility are the unique characteristics of the source to be detected, signal-to-noise ratio and the effect of reflections, distance and atmospheric affects. Discrimination is aided by identifiable spectral characteristics measured over time.

One of our cases was for a defendant in a murder trial who was able to reliably account for his whereabouts after midnight the night of a fatal shooting. After the prosecution had rested its case two people were chatting in the local beauty parlor. One recalled hearing two gunshots on the quiet evening of the murder at a distance of nearly a mile from the murder scene. She had not come forth earlier because she had read in the local paper that the murder took place much earlier in the evening. But the other person reported reading that the time of death had been called into question at trial. The defense reasoned that if the witness could reliably testify about hearing the gunshots at a time when the defendant was far from the murder scene, reasonable doubt might be established.

We conducted a simulation in the field at the gunshot source and listener receiver locations from the police report. The same type and caliber weapon used for the murder and the time of the shooting (1:00 a.m.) were selected. Calibrated digital audio tape recordings were made of the shooting. In order to facilitate queuing to the proper location of the quiet gunshot on the tape, the gunshot source was recorded electronically via walkie-talkie on one channel of the DAT tape while the receiver gunshot was recorded on the second channel.

The recording at a distance of nearly one-mile was so faint that we believed it was inaudible. That opinion was reached by observers in the field and confirmed later during playback of the recordings. A second test was conducted at a position halfway between the witness and the receiver on-axis with the original propagation path. This time, we agreed that the gunshot was definitely audible. Since the gunshot sound radiates hemisphericaly from the source, the sound level at the second recording location (half the distance between the original receiver location and the source location) was 6 dB above that of the first test. Some additional reduction in sound level might be expected at the higher frequencies from air absorption, but in this instance little high frequency energy remained for either recording.

The second test showed that the gunshot could have been heard if the signal-to-noise ratio of the gunshot to the background noise were 6 dB greater. This could have occurred if the background noise on the night of the shooting were 6 dB below that on the night of the test. Therefore our measurement represented the same signal-to-noise conditions that may have existed the night of the murder with a 6-dB quieter background noise environment. Weather history information indicated slightly more wind that may be argued to account for this difference in background sound.

4.2 Gunshot Signature

Another case of interest was that of the murder of a law enforcement officer on an American Indian reservation. The officer was shot during a drug raid, and the defendant claimed self-defense stating that the police officers fired first. The sequence of gunshots was recorded by a shoulder-mounted microphone and to a microcassette recorder, worn by one of the officers.

Among the first issues addressed by the court was whether the prosecution's expert could reliably determine from the microcassette recording which weapon was fired first. This was reviewed in California at a preliminary 'Frye hearing' where the issue was not the evidence itself, but whether the technology used by the plaintiff expert is valid. The broad criterion for evidence acceptance is whether or not the body of experts recognizes the particular type of evidence. The intent is to sort out premature science or junk science such as palm reading or soothsaying.

The recording in evidence was poor quality with sounds of the officer crawling for cover in the gravel and several short puff-sounding firearm reports. The duration of each report was just under two seconds. The recorder was a consumer-grade dictation-type recorder with automatic gain control. The Indians were armed with Ruger Mini-14 rifles and the police were using AR-15 rifles (the civilian version of the M-16 military rifle). The recording location relative to the shooting locations was unknown. Both rifles fire the same .223 caliber and 55-grain ammunition, and have similar barrel lengths.

The plaintiff expert testified first to his credentials, publications and experience. He then pointed to two enlarged time versus sound level plots and stated that, in his professional opinion, one plot was 'very indicative' of the Ruger Mini-14 and the other of the AR-15.

We were able to establish several facts:

- The entire gunshot signature lasted only a few microseconds, and the time domain plots for the extended period showed local reflections from the terrain and other objects, and revealed no information about the firearm used.

- The microcassette recorder was incapable of capturing the rapid rise time of a gunshot and therefore could not record the muzzle blast signature.

- The muzzle blast signatures of the two weapons, when properly recorded over a few microseconds, are expected to be nearly identical. There is nothing in the theory of muzzle blasts or N-wave propagation that would allow distinction between reports from these two weapons.

4.3 Gunshot timing

We were retained by the defense attorney for a California police department in a case alleging a wrongful death (fatal shooting) by the police; essentially the plaintiffs accused the police of an assassination. The evidence examined was a multi-track recorder, using VHS tape, which simultaneously time-coded and recorded various police communication channels. The two channels of interest in this case were police radio communications with the dispatcher and the 911-telephone line with the dispatcher.

The first dialog was from a person hysterically screaming to the dispatcher "…they're coming to kill my brother." The dispatcher was attempting to calm the caller and obtain as much information as possible. The dispatcher was able to solicit the location of the suspected assailants and was relaying that information in turn to the two policemen who had just arrived on the scene. After nearly another minute of dialog one of the officers said "…he's got an AK…". At that point there is a barrage of gunfire on the recording, most certainly from a rifle in full automatic mode.

The plaintiffs' explanation of the events put the alleged assailants at a location nearly equidistant from the police and the telephone caller. However, when we analyzed the timing of the first gunshot on the telephone track and on the police dialog track, we found a timing difference of more than 60 milliseconds. This timing difference showed that the police and the assailants were more than 65 feet apart, and disparaged the plaintiffs' account of the events.

5 APPLICATIONS

5.1 Sniper detection systems

Understanding of gunshot reports and N-waves have also helped in developing several sniper detection systems. Some of these systems use global positioning system (GPS) receivers to locate microphone locations within a few feet. These systems record N-waves using inexpensive low-gain microphones and accurately record the timing of projectile shock waves at the known receiver locations. A computer in the field automatically inputs the timing information from the multiple receiver locations to compute the sniper location. Muzzle blast information, if available (when no silencer is used by the sniper), supplements the N-wave information to locate the shooting source.[10]

5.2 Gunshot location

Gunshot location may be determined by the timing of the muzzle blast report recorded at three or more locations. A local computer determines the location from the difference in time that the report is received at the recording locations and from the speed of sound. Perhaps the best example of this technology is the ShotSpotter® system which uses three or more microphones distributed throughout a city or neighborhood to locate the source location of a gunshot. This system simply uses the time between gunshot detection and an assumed speed of sound to triangulate the source location by distance only (no directional information is required). This system is employed at several cities around the U.S. and is typically accurate to within 10 m (33 feet).

6 CONCLUSIONS

Gunshot analyses, like most forensic science, can reveal important information but is also subject to limitations. The sound level and spectrum of a muzzle blast is a complex phenomenon that can be approximated by the methods from ISO 17201-2. Shock waves from supersonic bullets behave like those from supersonic aircraft. Some shock wave characteristics of rifle bullets may be reliably predicted, and used to locate the origin of a gunshot. Gunshot analyses of recordings frequently cannot identify the type of firearm or caliber of ammunition, due largely to limitations of the recording equipment. The audibility of gunshots may be tested in field simulations in order to evaluate the credibility of witnesses' testimony. Finally, the timing of gunshots, when recorded simultaneously at known locations, can identify the source location.

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