Summary of Gun Shot Acoustics

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Audio recordings of gun shots can provide information about the gun location with respect to the microphone(s) and the speed and trajectory of the projectile. The principal difficulty when interpreting such recordings arises from reverberation (overlapping acoustic signal reflections) due to the gun shot sound reflecting off and diffracting around nearby surfaces.

Muzzle Blast

A conventional firearm uses a confined explosive charge to propel the bullet out of the gun barrel. The hot, rapidly expanding gases cause an acoustic blast to emerge from the barrel. The acoustic disturbance lasts 3-5 milliseconds and propagates through the air at the speed of sound (c). The sound level of the muzzle blast is strongest in the direction the barrel is pointing, and decreases as the off-axis angle increases.

A microphone located in the vicinity of the gun shot will detect the muzzle blast signal once the sound propagation travels at the speed of sound from the gun to the microphone position. However, the muzzle blast signal will also reflect off the ground and off other nearby surfaces, resulting in a complicated received signal consisting of multiple overlapping reflections.

Supersonic Projectiles: Shock Wave Considerations

Depending on the size of the charge, the mass of the bullet, and other factors, the bullet may be traveling at supersonic speed. A supersonic bullet causes a characteristic shock wave pattern as it moves through the air. The shock wave expands as a cone behind the bullet, with the wave front propagating outward at the speed of sound. The shock wave cone has an inner angle, $\theta_M = \arcsin(1/M)$, where $M = V/c$ is the *Mach Number*. The geometry is shown in Figure 1.

With a very fast bullet, M is large and θ_M becomes small, causing the shock wave to propagate nearly perpendicularly to the bullet's trajectory. For example, a bullet traveling at 3000 feet per second at room temperature has M=2.67, giving θ_M = ~22°. On the other hand, if the bullet is only slightly faster than the speed of sound, M is approximately unity, θ_M is nearly 90°, and the shock wave propagates nearly parallel to the bullet's path.

If two or more microphones are located at known locations within the path of the shock wave, the time of arrival difference(s) can be used to 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. If V is not known, then M and θ_M are also not known, and the bullet's trajectory cannot be determined exactly without additional spatial information.

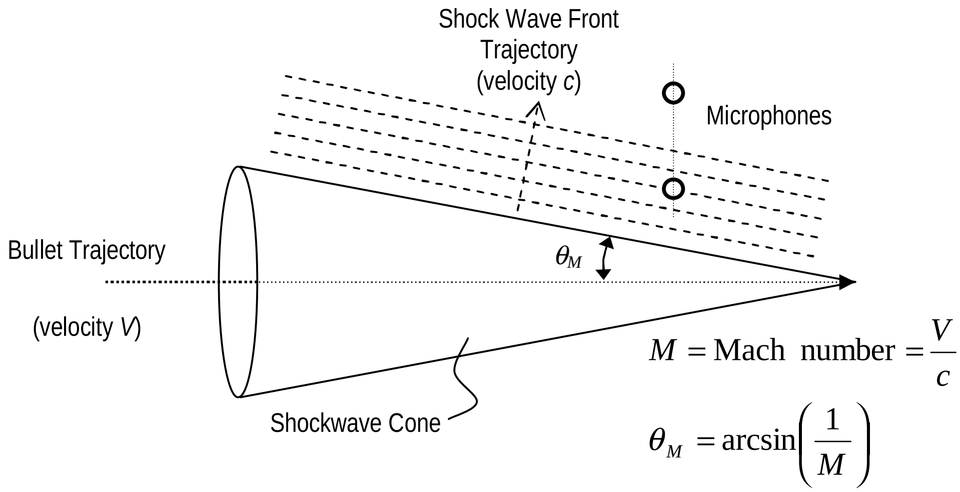

Figure 1: Supersonic Bullet Shock Wave Description

The acoustic shock wave from the bullet has a very rapid rise to a positive overpressure maximum, followed by a corresponding under-pressure minimum. As the shock wave propagates the nonlinear behavior of the air causes the pressure disturbance to form an "N" shape with a rapid onset, a ramp to the minimum pressure, and then an abrupt offset. The time interval of the "N" wave between the over- and under-pressure is proportional to the size of the projectile. A typical bullet a few centimeters long has an intershock interval of less than 200 µsec, as shown in Figure 2.

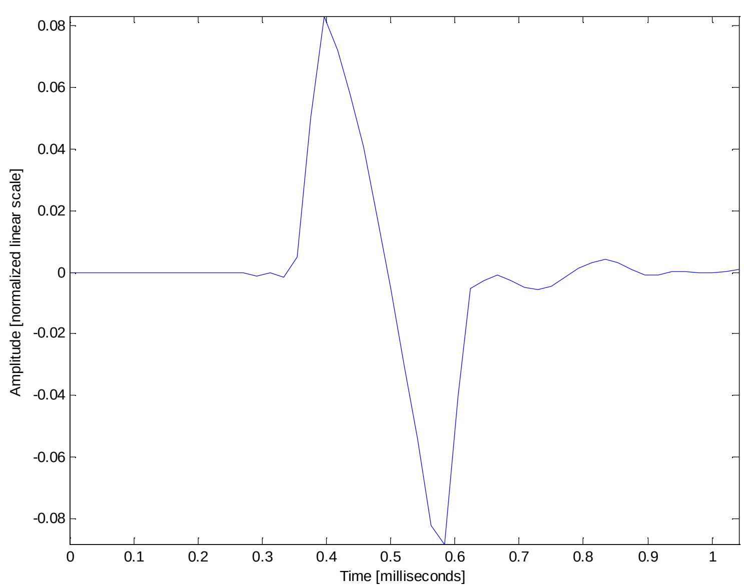

Figure 2: Shock Wave Recording ("N" Wave)

If solid surfaces are present nearby, the passing shock wave cone will be partially absorbed and partially reflected by the surface. Thus, a microphone in the vicinity will pick up both the original shock wave and the reflected shock wave with a delay corresponding to the path length difference. The ground reflection is depicted in Figure 3.

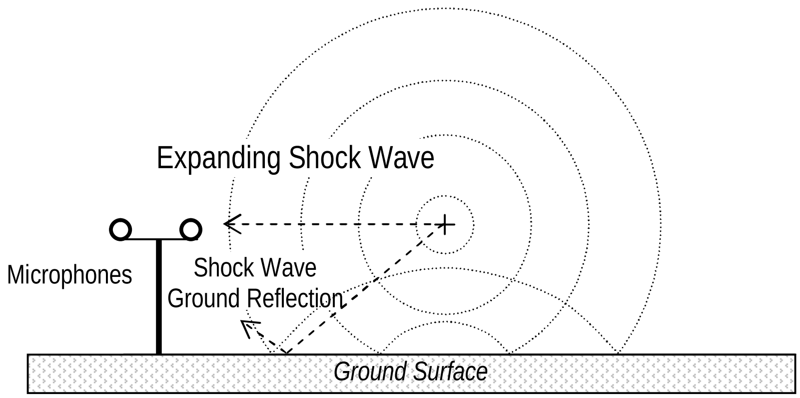

Figure 3: Shock Wave Ground Reflection (elevation view, not to scale, bullet into the page)

Example Test Recording

A Winchester 308 rifle was fired horizontally in a direction perpendicular to the plane of two omnidirectional microphones mounted one foot apart (0.305 meters) and 1.6 meters above the ground. The rifle was fired from shoulder height (approximately 1.6 meters above the ground) at a distance of 6.3 meters from the plane of the microphones. The bullet crossed the microphone plane 3.7 meters from the nearest (“left”) microphone.

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°. The geometry is shown in Figure 4.

The predicted acoustic result begins with the bullet speeding away from the muzzle along path *A* at more than 2.5 times the speed of sound, trailing its 23.2° shock wave cone.

The shock wave front itself, expanding outward from the bullet’s path at the speed of sound, will propagate away from the bullet’s course in a direction parallel to paths *B* and *B*’.

The shock wave ray that reaches the microphone is launched when the bullet reaches position *X*. Thus, the total time between the gun shot and the shock wave arrival at the microphone consists of the bullet’s time-of-flight at velocity *V* from the muzzle to point *X*, plus the ensuing shock wave ray propagation at the speed of sound along ray path *B*. Geometrically, this total time is equal to the propagation time at the speed of sound along path *B*’.

The ground reflection of the shock wave ray will propagate at the same azimuth as path *B*, but along the longer path from the muzzle to the ground and back up to the microphones.

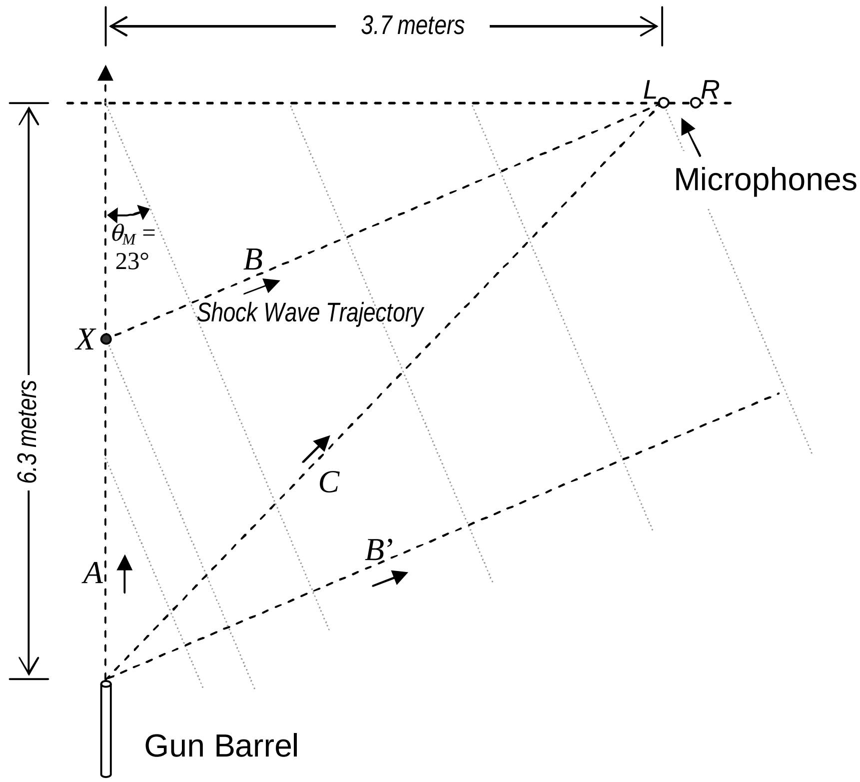

Figure 4: Geometry of Test Recording (plan view, not to scale)

The sound of the muzzle blast itself will travel directly from the gun to the microphones along path *C*. The ground reflection of the muzzle blast arrives later due to the longer propagation distance from the muzzle to the ground and then back up to the microphones.

The *predicted* propagation times for the shock wave and muzzle blast arrivals at the microphones are shown in Table 1.

TABLE 1: *Theoretical propagation behavior*

Path	Length	Time	
Bullet: muzzle to *X*	4.75 m	5.71 ms	sum = 18.0 ms
Shock: path *B* (*X* to mic *L*)	4.35 m	12.3 ms	
Shock: path *B'*	5.91 m	18.0 ms	
Shock: ground reflection to *L*	6.63 m	20.2 ms	
Shock: microphone *L* to *R*	0.280 m	0.855 ms	
Blast: path *C* (muzzle to *L*)	7.35 m	22.4 ms	
Blast: ground reflection to *L*	7.93 m	24.2 ms	
Blast: microphone L to R	0.154 m	0.470 ms	

The two-channel audio recording obtained from this configuration is shown in Figure 5. Using the arrival of the initial shock wave as the time reference, the measured time intervals and the percent discrepancy between the measured and predicted values are shown in Table 2. The microphone signals were digitized with a 48 kHz sample rate per channel so the timing accuracy is limited to 0.0208 milliseconds (1/48000), but the agreement between the predictions and the measurement are very good, which appears to validate the geometrical acoustics model.

TABLE 2: ***Measured acoustic timing***

Interval	Measured	Discrepancy
• Shock: reflection relative arrival	2.23 ms	-0.037 ms (-1.7%)
, Shock: microphone *L* to *R*	0.833 ms	0.022 ms (2.6%)
ƒ Blast arrival relative to Shock	4.39 ms	0.017 ms (0.38%)
„ Blast: reflection relative arrival	1.80 ms	0.069 ms (3.8%)
… Blast: microphone L to R	0.479 ms	-0.005 ms (-1%)

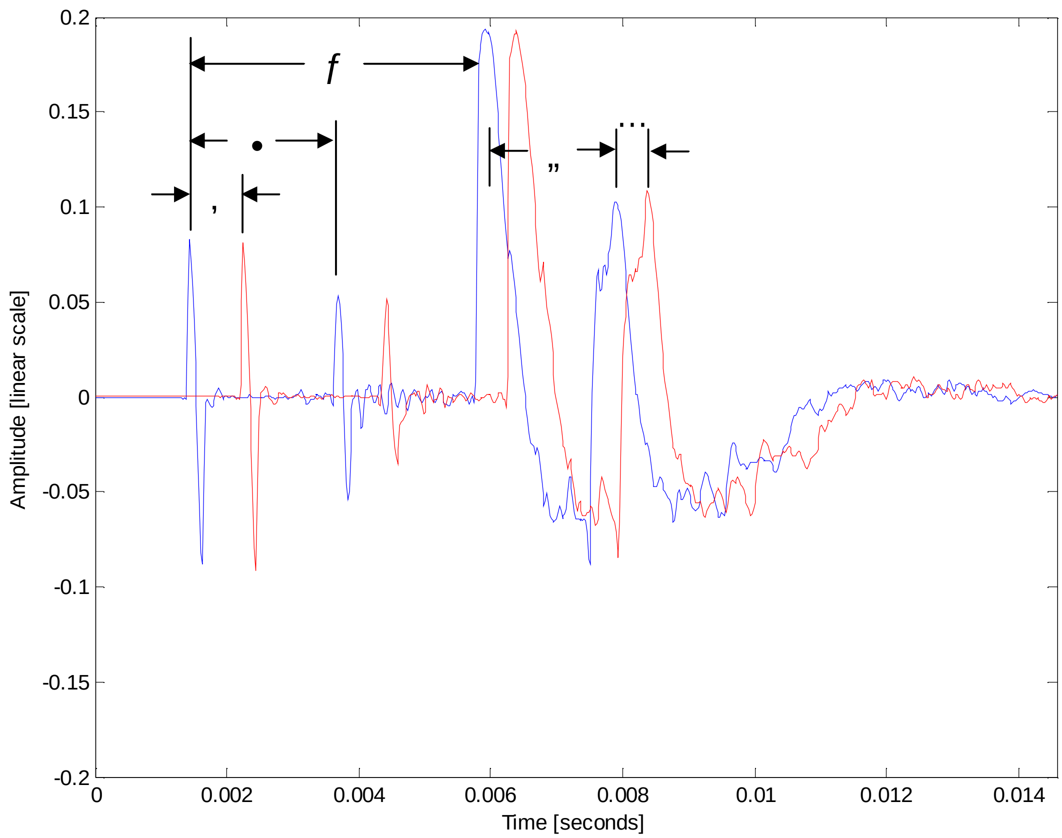

Figure 5: Two-Channel Audio Recording (Blue=left, Red=right)

Concluding Comments

- If the muzzle is pointed away from the microphones at an angle such that the shock wave cone does not reach the microphones, only the muzzle blast will be observed.
- The muzzle blast sound appears to be highly directional. Figure 6 shows the acoustic recording obtained when the bullet's trajectory passes very close to the microphones, causing the shock wave reflections and the muzzle blast to arrive essentially simultaneously in both channels at the microphones. Figure 7 shows the acoustic recording when the muzzle is facing away from the microphones: no shock wave is detected and the muzzle blast is reduced compared to the direct shot in Figure 6.

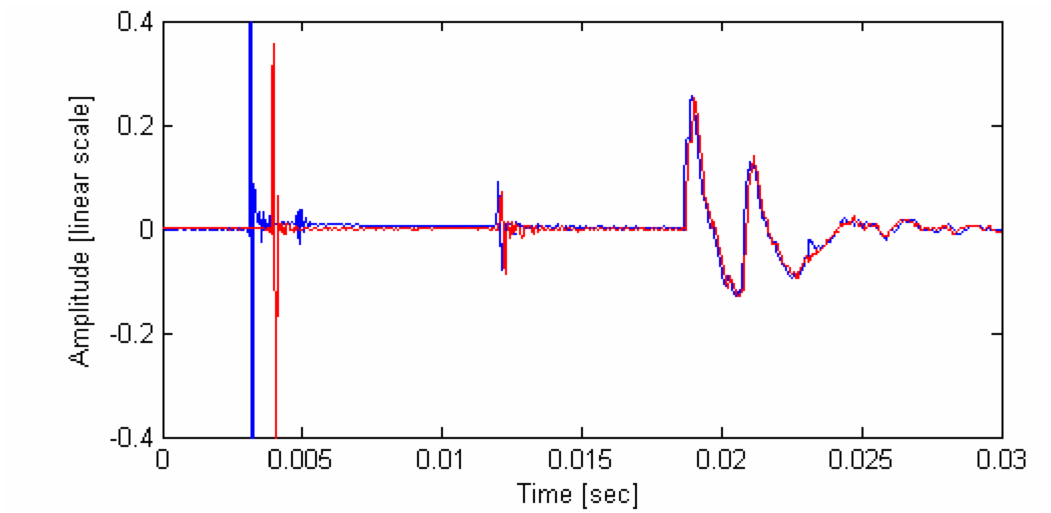

Figure 6: Gun Shot Recording, Bullet Trajectory Passing Close to Microphone

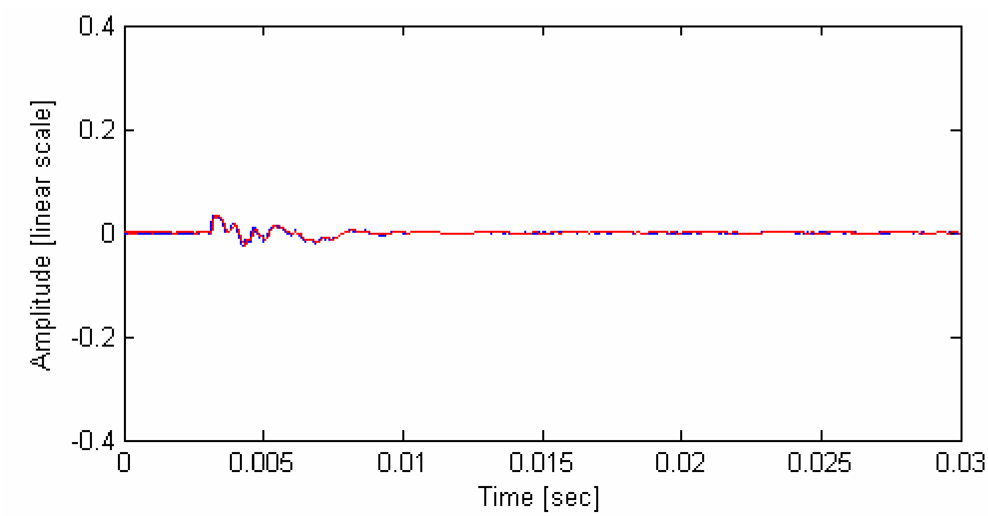

Figure 7: Gun Shot Recording with Microphones Behind the Rifle

- At distances far from the bullet's trajectory, the shock wave will have expanded sufficiently that it may not be detectable compared to ambient noise.
- The projectile will slow down due to friction with the air. Thus, the Mach Number will decrease and the shock wave cone will widen as the bullet travels down range. This effect may be useful in determining the firing location if several acoustic sensors are deployed along the bullet's trajectory.
- If there is no direct acoustic path between the muzzle and the microphone, the received signal will be characterized by reflections and diffraction of the gun shot sound by nearby surfaces and obstacles. In this situation the audio recording will likely give more information about the acoustic surroundings rather than the firearm or the projectile. Deconvolving the gun shot from the reflected sound and the reverberant clutter is generally a challenging problem.
- A sub-sonic rifle or handgun produces only the muzzle blast signal. The subsonic bullet does not produce significant sound as it propagates through the air. An example recording of a handgun (HK USP compact, 40 Smith and Wesson, Federal Hydroshock) corresponding to the gun and microphone geometry of Figure 4 is shown here in Figure 8. Comparing the handgun recording in Figure 8 to the previously described rifle recording of Figure 5, the handgun shows no shock wave signature and muzzle blast that is quieter and shorter in duration than the rifle shot.

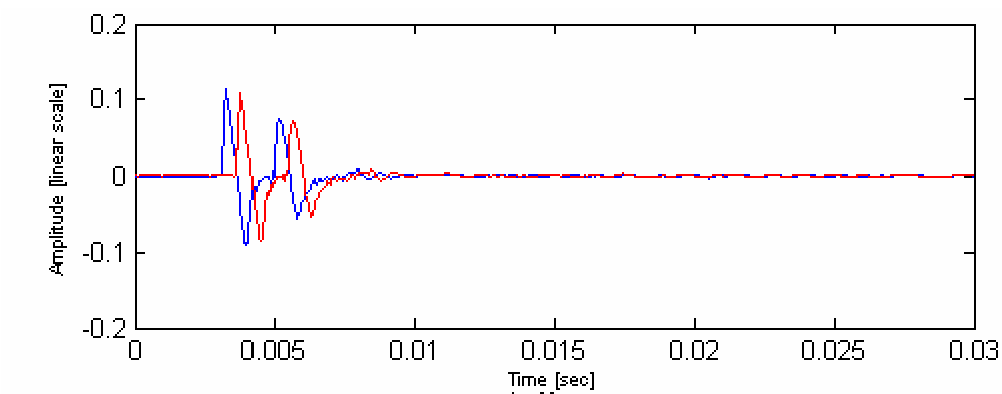

Figure 8: Hand Gun Recording (same position as rifle data in Figure 4 and Figure 5)