Audio Engineering Society

Convention Paper 8494

Presented at the 131st Convention
2011 October 20–23 New York, NY, USA

Acoustical modeling of gunshots including directional information and reflections

Robert C. Maher

Electrical & Computer Engineering, Montana State University, Bozeman, MT 59717-3780 USA
rob.maher@montana.edu

ABSTRACT

Audio recordings of gunshots exhibit acoustical properties that depend upon the geometry and acoustical characteristics of nearby reflecting surfaces and the relative orientation of the firearm with respect to the recording microphone. Prior empirical studies have demonstrated the basic principles of gunshot recordings near the firearm and near the target. This paper describes an experiment to model the directional characteristics and reflections of several firearm types for a set of test configurations. The results show that reflections and reverberation can be a significant portion of the total acoustic energy received at the microphone.

1. INTRODUCTION

Audio forensic analysis of recorded gunshots may play an important role in crime scene reconstruction [1]. Gunshot-related acoustics may include the subtle sound of the firearm's mechanical action, the loud muzzle blast, and in the case of supersonic projectiles, the shock wave signature of the bullet [2-9]. These direct sounds are almost always accompanied by the arrival of reflected, diffracted, and reverberated sound from the ground, adjacent surfaces, and other nearby obstacles.

A conventional firearm uses a confined combustive charge to propel the bullet out of the gun barrel. The sound energy emanating from the barrel is referred to as the muzzle blast, and typically lasts for less than 3 milliseconds [6]. The muzzle blast sound is emitted from the gun in all directions, but with a strongly directional characteristic in which the majority of the acoustic energy is expelled in the direction the gun barrel is pointing [8, 9]. 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. The received acoustic signal will thus exhibit propagation effects, multi-path reflections, and reverberation. The gunshot audio recording will typically include the superposition of the muzzle blast direct sound, the reflection of the muzzle blast from nearby surfaces, and ultimately reverberation from higher-order reflections several milliseconds after the direct sound and first-order reflections. If the projectile is supersonic, the recording may also contain evidence of the bullet's acoustic shockwave and reflections of the shockwave from the surrounding surfaces [6].

It is appealing theoretically to consider modeling gunshot acoustics simply by convolving a single recording of a gunshot sound with the impulse response of the space in which the recording is made. Assuming the acoustical propagation behavior obeys linearity principles, such a strategy seems straightforward and easy to implement. However, the simple impulse response convolution idea includes the implicit assumption that the input signal is an omnidirectional point source, which is not generally the case for firearms. Thus, acoustical modeling of recorded gunshots must also take into account the directional characteristics of the firearm and the corresponding directional variation in reflections and reverberation.

The study reported in this paper involves acoustical modeling of gunshot acoustics. A set of gunshot audio recordings have been obtained for a variety of firearms and a range of directional azimuths with respect to the barrel [8]. Unlike prior modeling work that has used a single gunshot recording and convolved it with a single impulse response of a chosen acoustical geometry, the work reported in this paper uses the empirically obtained directional characteristic of each firearm and a compound image-source method to simulate the acoustic signal recorded at an arbitrary recording location.

This work is intended to demonstrate several principles that are critical to forensic interpretation of gunshot acoustic evidence, emphasizing the need for forensic examiners to be wary of common assumptions that can oversimplify the complexity of the acoustic evidence.

The remainder of this paper is organized as follows. First, an example recording that includes a single significant ground reflection is presented, including the geometrical acoustics that explain the recorded signal. Next, an anechoic directional recording of the initial portion of the gunshot from the same firearm is used to create a plausible simulation of the basic geometry, and the simulation is compared to the actual recording. Finally, several simulations including the firearms' directional characteristics for specific geometries are presented and discussed.

2. GUNSHOT EXAMPLE: SINGLE REFLECTION

Figure 1 is an example gunshot recording obtained at a shooting range. The firearm used was a rifle chambered for .308 Winchester cartridges. The recording was obtained using an omnidirectional electret condenser microphone (DPA 4003), a corresponding high voltage preamplifier (HMA 5000), and a digital audio recorder operating with 16-bit resolution and a 48 kHz sample rate per channel. Note that the zero time reference in the figure is assigned arbitrarily. The microphone and the rifle were 8.4 meters apart and 1.6 m above the sandy, frozen surface of a firing range. The gunshot was directed parallel with the ground surface in a trajectory that passed approximately 0.5 m from the microphone.

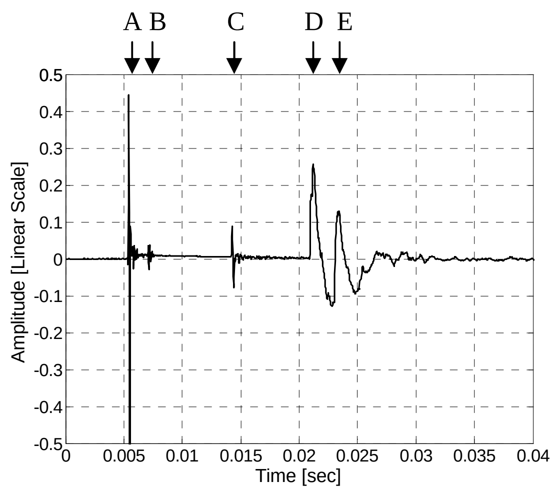

Figure 1: Example gunshot recording with ground reflection; .308 rifle fired toward the microphone from a distance of 8.4 meters; rifle and microphone 1.6 meters above the ground.

The recording includes several distinct events. First, at approximately 5.5 ms the acoustic shock wave caused by the passage of the supersonic bullet near the microphone is visible (A), followed by a small shock wave reflection presumably from the microphone bracket and stand at 7 ms (B). A larger and more distinct shock wave reflection is seen at 14 ms (C), corresponding to the first ground reflection. The muzzle blast arrives at time 21 ms (D), followed by the reflection of the muzzle blast from the ground at about 23 ms (E). The arrival timing of the sounds and reflections matches the geometrical predictions taking into account the bullet speed (831.5 m/s) and the speed of sound (328 m/sec for approximately -7°C) [5].

For comparison, Figure 2 is an example of the same type of rifle shot recorded with the firearm and the microphone elevated to provide a longer interval before the arrival of the first ground reflection. The anechoic portion of the recording is shown in the figure, with an extrapolated line depicting the post-shot pressure relaxation. The spacing between the firearm and the microphone was 3 m rather than 8.4 m, so the time gap between the bullet's shock wave and the arrival of the muzzle blast is shorter in Figure 2 than in Fig. 1.

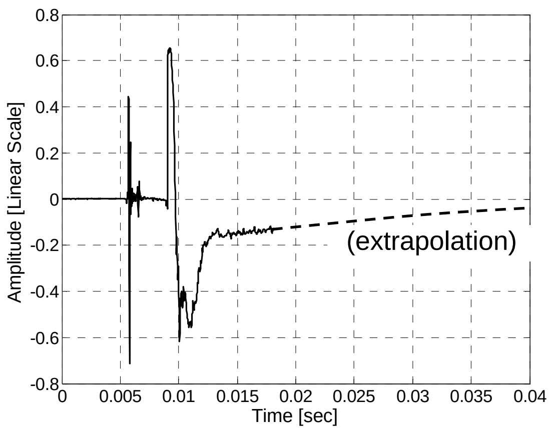

Figure 2: Example quasi-anechoic gunshot recording; .308 rifle fired toward the microphone from a distance of 3 m; rifle and microphone 3 m above the ground.

Using the quasi-anechoic recording from Fig. 2 as the starting point for the direct sound path from firearm to microphone, it is possible to simulate the shock wave and muzzle blast ground reflections seen in the recording of Fig. 1 if we also know the directional sound characteristics of the firearm and can estimate the reflection, attenuation and delay differences. For the geometry used for the recording shown in Fig. 1, the ground reflection corresponds to sound emitted approximately 20 degrees off-axis compared to the barrel. An available recording of the waveform for about 20° off-axis is shown in Figure 3.

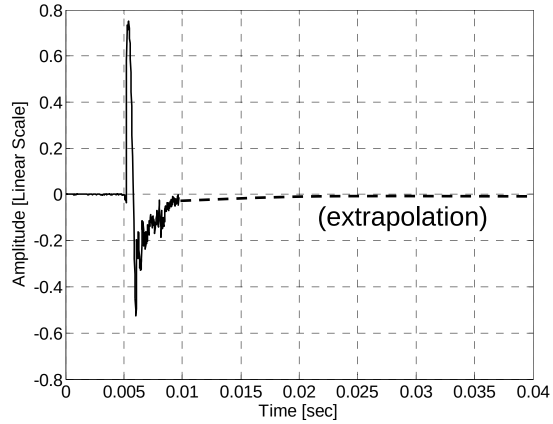

Figure 3: Example quasi-anechoic gunshot recording; .308 rifle recorded off-axis by more than 20°; projectile's shock wave does not reach the microphone.

Note that the off-axis muzzle blast for this particular rifle has a more rapid decay than the on-axis blast [8].

The simulation process consists of several steps:

- Separate the projectile's shock wave and muzzle blast in the anechoic recording.
- Calculate the relative time-of-arrival of the direct sound and the ground reflection using geometric acoustics [4, 5, 6].
- Calculate the off-axis azimuth for the reflection path, and select the corresponding muzzle blast waveform [7, 8, 9].
- Calculate the attenuation due to spherical spreading.
- Calculate the attenuation due to an estimate of the ground surface reflection coefficient.
- Shift and overlap-add the direct and reflected components.

The result of this simulation/modeling process using the quasi-anechoic recordings from Fig. 2 and Fig. 3 is shown in Figure 4. The model results compare favorably to the actual recording shown in Fig. 1.

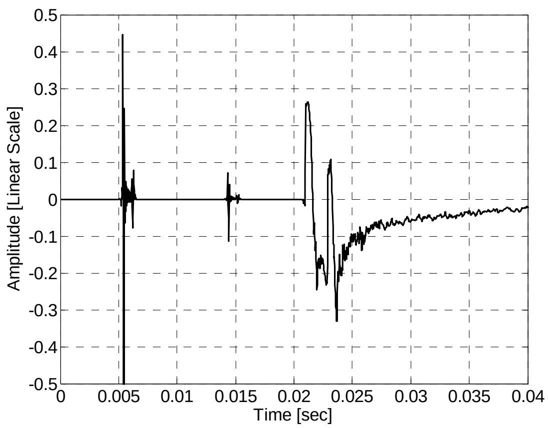

Figure 4: Modeled gunshot recording with simulated ground reflection; simulation of a .308 rifle fired toward the microphone from a distance of 8.4 m; rifle and microphone 1.6 m above the ground.

The single reflection simulation depicted in Fig. 4 indicates several concerns for audio forensics. First, as noted in prior studies, the durations of the individual shock wave and muzzle blast events are quite brief, with the entire acoustical signature lasting a few tens of milliseconds. Therefore, analyses treating gunshot audio on the time scale of hundreds or thousands of milliseconds will inherently contain predominantly reflected and reverberated sound. Second, the waveform details depend quite intimately on the relationship between the duration of the shock wave and muzzle blast events and the relative arrival time of the reflections. Finally, even for a single reflection the total acoustical energy received by the microphone includes a significant contribution from the ground reflection, and therefore any automatic identification system will need to consider the effect of this reflected energy in both the time and frequency domains.

3. GUNSHOT SIMULATION WITH MULTIPLE REFLECTIONS

Based upon the results for a single ground reflection, additional simulations can be created for more complicated and realistic scenarios using the image source method [10-13] or other acoustical modeling techniques. The important remark is that such models need to include the directional characteristics of the firearm so that the reflected energy is accounted for properly [13].

To emphasize this point, consider the following example simulations involving an “alley” with several reflecting surfaces, as depicted as a plan view in Figure 5. In this simulation example a .357 Magnum handgun is located 10 m from the west wall and 3 m from the north wall, oriented so that its barrel is pointing to the west and 1 meter above the ground, while the simulated omnidirectional microphone is located 15 m from the west wall and 3 m from the south wall, also 1 m above the ground. The surrounding north, west, and south wall surfaces are modeled here as hard, simple reflecting planes with absorption 0.1, the ground is modeled also as a simple reflector with absorption 0.05, and the east and above portions are modeled as open areas (no reflection). The geometry results in the microphone being located 6.4 m from the simulated firearm and at azimuth 141° with respect to the barrel. Measurements of the .357 Magnum handgun show that the level difference between the on-axis muzzle blast and the level behind the firearm is 10-15 dB SPL [8].

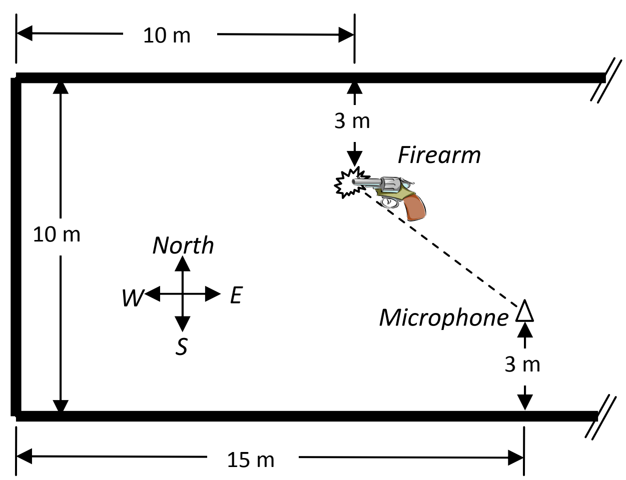

Figure 5: Plan view for multi-reflection acoustical simulation: modeled “alley” scenario.

Using the image source method [10, 11], Table 1 summarizes the direct and reflected components and the off-axis angles corresponding to the direct sound and reflections impinging on the microphone position during the first 100 ms.

The empirical data for the .357 Magnum handgun is summarized in Figure 6, which shows recordings of the muzzle blast as a function of azimuth with respect to the barrel.

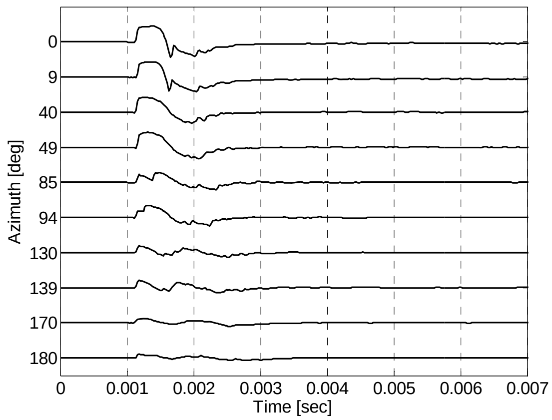

Figure 6: Gunshot waveforms (pressure amplitude vs. time) for a .357 Magnum handgun as a function of azimuth.

Note that the gunshot waveforms and amplitudes shown in Fig. 6 vary substantially as a function of azimuth. Therefore, it is important to include the directional characteristics when simulating the direct and reflected pressure waveforms.

The resulting simulated microphone signal is shown in Figure 7, based on accumulating the modeled contributions from each image source, taking into account the directional characteristics of the firearm, the modeled reflection coefficients, and the natural amplitude attenuation due to spherical spreading.

Note that the complexity of the simulated signal has increased geometrically due to the initial and compound reflections, many of which overlap. Because the simulated firearm is pointed away from the microphone, the initial sound arrival is relatively low in amplitude because it corresponds to the muzzle blast emanating at ~140° azimuth with respect to the barrel. On the other hand, the relatively high amplitude just prior to 80 ms is due to the coincident arrival of several reflections from surfaces located west of the firearm, due to the nearly on-axis (22° azimuth) high amplitude muzzle blast.

Now consider what occurs when we calculate the same relative geometry of simulated firearm and microphone as was shown in Fig. 5, but with the firearm oriented *east*, rather than *west*. This changes the directional characteristics of the direct sound and reflections, but does not alter the timing from geometrical acoustics. The model results are shown in Figure 8.

Source/Image coordinates [m]			Distance to microphone [m]	Azimuth w.r.t. muzzle [deg]	Surface factor
x	*y*	*z*			
10	7	1	6.40	141	1.00
10	13	1	11.18	117	0.90
10	-7	1	11.18	117	0.90
10	13	-1	11.36	117	0.86
10	-13	1	16.76	107	0.81
10	-13	-1	16.88	107	0.86
10	27	1	24.52	102	0.81
10	27	-1	24.60	102	0.77
-10	13	1	26.93	22	0.90
-10	-7	1	26.93	22	0.90
-10	13	-1	27.00	22	0.86
-10	-7	-1	27.00	22	0.86
-10	-13	1	29.68	33	0.90
-10	-13	-1	29.75	33	0.77
10	33	1	30.41	99	0.73
10	-27	1	30.41	99	0.73

Table 1: Approximate direct and image source information for the first 100 ms.

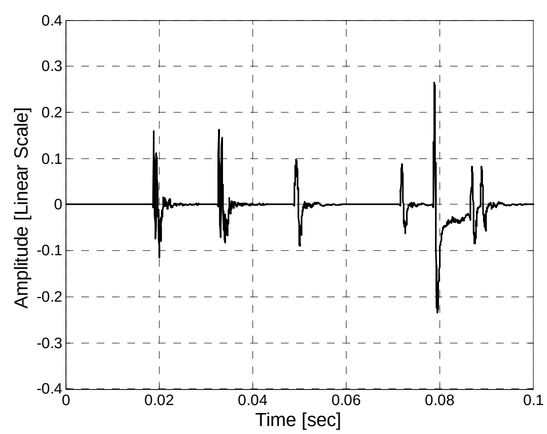

Figure 7: Modeled gunshot recording, first 100ms, with simulated reflections for geometry depicted in Figure 5; .357 Magnum handgun.

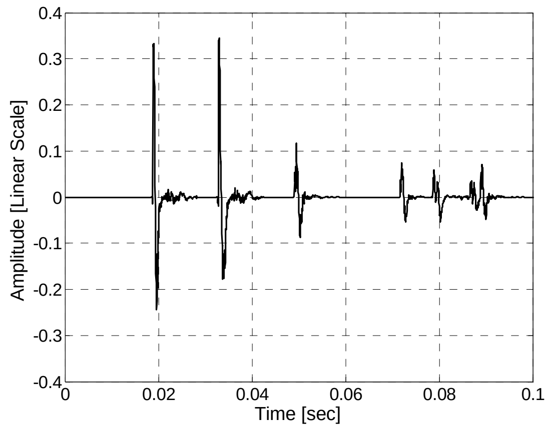

Figure 8: Modeled gunshot recording, first 100ms, with simulated reflections for geometry depicted in Figure 5, except with barrel pointing *east* rather than west; .357 Magnum handgun.

The comparison of Fig. 7 and Fig. 8 shows the similarities and differences between two simulated recordings in the same space, but with the orientation of the firearm reversed. If the simulation had *not* included the directional characteristics of the firearm, the signals depicted in Fig. 7 and Fig. 8 would be the same because the geometrical modeling is the same: including the empirically determined directional information results in a noticeably different outcome.

In the configuration simulated in Fig. 8, the firearm is pointed in the general direction of the microphone, while the reflections from the north and west correspond to the lower level off-axis direction with respect to the firearm's barrel. For audio forensics, this comparison could conceivably allow determination of the likely orientation of one or more firearms in a monophonic audio recording, or provide information that might disambiguate the order in which two or more firearms were discharged.

4. CONCLUSION

The study reported in this paper uses the directional characteristic of a firearm and a compound image-source method to simulate the acoustic signal recorded at an arbitrary recording location. This approach takes into account the significant differences in sound pressure waveforms and levels between on-axis and off-axis reflection geometries.

As demonstrated with the two simulation examples in Section 3, the orientation of the firearm can have a significant effect upon the received waveform. This effect is not predicted by simple convolution of a single gunshot recording with a single impulse response. Thus, this work is intended to emphasize the need for forensic examiners to be wary of common assumptions that can oversimplify the potential complexity of acoustic evidence. This caveat may be particularly important for the design of automatic gunshot classification systems.

5. ACKNOWLEDGEMENTS

The assistance of Prof. Steven R. Shaw in making the original gunshot audio recordings is gratefully acknowledged. The assistance of the Montana State University Red Bluff Research Ranch, Mr. Pete Olind, ranch manager, is also greatly appreciated.

6. REFERENCES

[1] Maher, R.C. "Audio forensic examination: authenticity, enhancement, and interpretation," IEEE Signal Processing Magazine, vol. 26, no. 2, pp. 84-94, March 2009.

[2] Koenig, B.E., Hoffman, S.M., Nakasone, H., and Beck, S.D., "Signal convolution of recorded free-field gunshot sounds," J. Audio Eng. Soc., vol. 46(7/8), pp. 634-653, July/August 1998.

[3] Freytag, J.C., and Brustad, B.M., "A survey of audio forensic gunshot investigations," Proc. AES 26th International Conf., Audio Forensics in the Digital Age, pp. 131-134, July 2005.

[4] Maher, R.C. "Modeling and signal processing of acoustic gunshot recordings," Proc. IEEE Signal Processing Society 12th DSP Workshop, Jackson Lake, WY, pp. 257–261, Sept. 2006.

[5] Maher, R.C. "Acoustical characterization of gunshots," Proc. IEEE SAFE 2007: Workshop on Signal Processing Applications for Public Security and Forensics, Washington, D.C., pp. 109–113, April 2007.

[6] Maher, R.C. and Shaw, S.R. “Deciphering gunshot recordings,” Proc. Audio Eng. Soc. 33rd Conf., Audio Forensics—Theory and Practice, Denver, CO, pp. 1–8, June 2008.

[7] Rasmussen, P., Flamme, G., Stewart, M., Meinke, D., and Lankford, J., "Measuring recreational firearm noise," Sound & Vibration, pp. 14-18, August 2009.

[8] Maher, R.C. and Shaw, S.R. "Directional aspects of forensic gunshot recordings," Proc. Audio Eng. Soc. 39th Conf., Audio Forensics—Practices and Challenges, Hillerød, Denmark, pp. 1-6, June 2010.

[9] Beck, S.D., Nakasone, H. and Marr, K.W. “Variations in recorded acoustic gunshot waveforms generated by small firearms,” J. Acoust. Soc. Am., vol. 129, no. 4, pp. 1748-1759, April 2011.

[10] Allen, J.B. and Berkley, D.A. “Image method for efficiently simulating small-room acoustics,” J. Acoust. Soc. Am., vol. 65, no. 4, pp. 943-950, April 1979.

[11] Borish, J. “Extension of the image model to arbitrary polyhedra,” J. Acoust. Soc. Am., vol. 75, no. 6, pp. 1827-1836, June 1984.

[12] Stephenson, U., “Comparison of the mirror image source method and the sound particle simulation method,” Applied Acoustics, vol. 29, no. 1, pp. 35-72, 1990.

[13] Chen Z. and Maher, R.C. "Addressing the Discrepancy Between Measured and Modeled Impulse Responses for Small Rooms," Preprint 7239, Proc. 123rd Audio Engineering Society Convention, New York, NY, pp. 1-14, October, 2007.