Audio Engineering Society

Convention Paper 9634

Presented at the 141st Convention
2016 September 29–October 2 Los Angeles, USA

Wideband audio recordings of gunshots: waveforms and repeatability

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ABSTRACT

For the purposes of audio forensics research we have obtained multi-channel acoustical recordings of gunshots under controlled conditions for several firearms. The recordings are made using an elevated platform and an elevated spatial array of microphones to provide quasi-anechoic directional recordings of the muzzle blast. The consistency and repeatability of gunshot sounds are relevant to many areas of forensic analysis. This paper includes a description of the recording process and a summary comparison of the acoustical waveforms obtained from ten successive shots from the same firearm by an experienced marksman. Practical examples and applications are presented.

1 Introduction

This paper describes our current work to utilize special apparatus and methodology for scientific and repeatable collection of firearm acoustical properties, including the important direction-dependence of each firearm's sound field.

We have developed a standard procedure for cataloging firearm acoustical characteristics, and a database of acoustical signatures as a function of azimuth for a variety of common firearms and types of ammunition [1]. The acoustical characteristics of a firearm depend upon the type of gun and ammunition, and the azimuth with respect to the gun barrel. Forensic gunshot acoustical analysis must account for the overall sound level, the duration, and the angular dependence for comparison to the recorded evidence.

Criminal and civil investigations increasingly draw upon audio forensic evidence and interpretation [2]. This increase is due to the growing number of law enforcement vehicles equipped with mobile video and audio recorders, coupled with the increasing percentage of law enforcement officers who carry personal audio recording devices while on duty either by agency mandate or by the officer's personal choice. One aspect of the ubiquitous presence of audio recorders is the increasing likelihood that gunshots and other firearm sounds will be captured by these mobile recording systems.

While the availability of recorded acoustic evidence of firearm incidents is often helpful to an investigation, there are many issues and details that must be addressed. The primary issue is that the acoustical characteristics of gunshots are currently little understood in an objective sense by many law enforcement investigators and acoustical consultants, so there is the possibility of unscientific assumptions, interpretations, and testimony. Other issues for audio forensic examination of gunshot recordings include (a) the inability of common mobile phones and personal audio recorders to record intense acoustical sounds such as gunshots, (b) the acoustical variability of successive gunshot sounds even from a single firearm under similar conditions, and (c) the effects of the recording environment (diffraction, reflection, and reverberation) upon reliable audio forensic analysis of gunshot incidents [3, 4].

As we first reported last year at the 139th AES convention in New York [1], we have created a special test rig containing twelve omnidirectional instrumentation microphones (high voltage 1/8" diaphragm condenser mics with 140 kHz bandwidth and 190 dB SPL capability), placed at approximately 15 degree intervals on a semicircular (180 degree) arc of 3 meter radius. A high speed (500 kHz per channel) multichannel 16-bit digital audio recorder serves each microphone. Each firearm under test is fired from the center of the arc while the microphone system simultaneously and synchronously records the acoustical waveforms from each angular position. The firearm shooting position and the microphone rig are both elevated 3 meters off the ground of the shooting range so that there is a time delay between the arrival of the direct sound at the microphones and the arrival of the first reflected sound from the ground. The delayed arrival of the first reflection ensures that the entire muzzle blast is recorded anechoically [5].

This paper reports our analysis of the consistency and repeatability of successive gunshots from two specific firearms recorded with this system: a .308 rifle and a Glock 19 handgun.

2 Firearm examples: rifle and handgun

Conventional firearms have a barrel to direct the bullet and a compartment, the *firing chamber*, to hold the ammunition *cartridge* prior to shooting. The cartridge consists of a casing that contains the gunpowder (propellant) and the primer at the back end, and the bullet at the front end. The firing pin of the trigger mechanism strikes the primer, igniting it and causing rapid combustion of the gunpowder. The rapidly expanding hot gas from the combustion expands the cartridge case to seal the bore of the barrel, and the resulting chamber pressure forces the bullet down the barrel and out of the muzzle. The expanding gas behind the bullet emerges from the barrel as an intense pressure impulse, causing a loud acoustical report known as the *muzzle blast*.

The muzzle blast acoustical characteristics depend upon the type and size of the firearm, the characteristics of the ammunition, the direction with respect to the barrel axis, the presence of acoustical reflections from nearby surfaces, and diffraction from nearby obstacles [6, 7].

If the bullet is traveling at supersonic speed, a ballistic shockwave (a miniature "sonic boom") is produced. The speed and size of the projectile and the trajectory of its travel downrange determine the characteristics of the shockwave [8].

The two firearms chosen for this experiment to compare shot-to-shot consistency are a rifle (Surgeon Rifles) chambered in .308 Winchester ammunition, and a handgun (Glock 19) chambered in 9x19mm ammunition.

Figure 1 shows an example of the on-axis muzzle blast recording at 3 meters from the firearm for the .308 rifle, and Figure 2 shows the muzzle blast for the 9mm handgun, obtained using the quasi-anechoic system with 500kHz sampling rate.

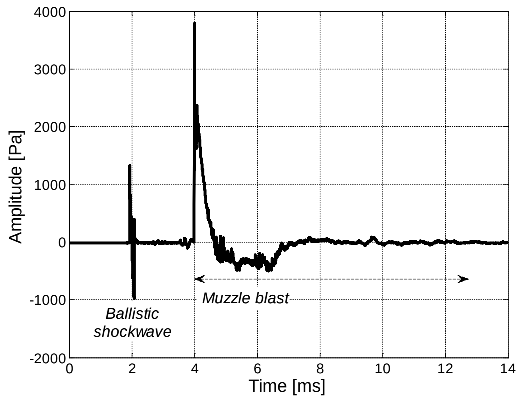

Figure 1: Recording of .308 rifle shot, 3 meters on-axis, no reflections. The initial trace is the ballistic shockwave from the supersonic bullet.

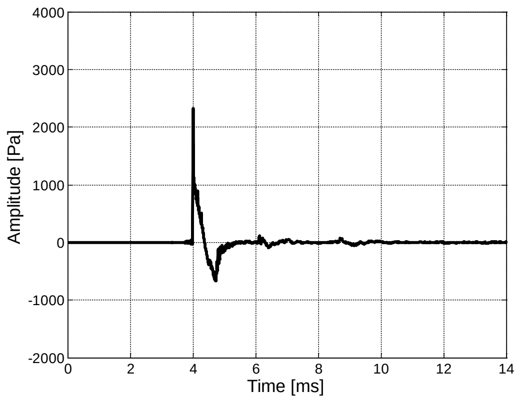

Figure 2: Recording of 9mm handgun shot, 3 meters on-axis, no reflections.

The muzzle blast portion of the rifle and handgun shots show similar general behavior, with an abrupt spike as the muzzle blast wave arrives at the microphone, then a positive-pressure phase and a negative-pressure phase, followed by additional pressure fluctuations as the muzzle blast energy dies away. The amplitude and duration of the rifle blast are greater than for the handgun.

Figures 3 and 4 show an example of the muzzle blast recordings from 81° off-axis (i.e., off to the side of the firearm) at 3 meters for the .308 rifle and the 9mm handgun, respectively, obtained using the quasi-anechoic system with 500kHz sampling rate. Note that the muzzle blast is reduced in amplitude and acoustic energy when observed off-axis compared to the on-axis recording. Also note that the geometry of the ballistic shockwave trailing the .308 rifle's bullet does not reach the microphones off to the side or to the rear of the gun.

3 Consistency of recorded gunshots

We recorded ten successive shots from the rifle and from the handgun using the quasi-anechoic system. The marksman hand-held the firearms during the testing, aimed at a target approximately 50 meters down range, and manually repositioned the firearm between shots. The guns were not mechanically restrained in any fashion so it is likely that there was some incidental random discrepancy in aim and muzzle position from one shot to the next.

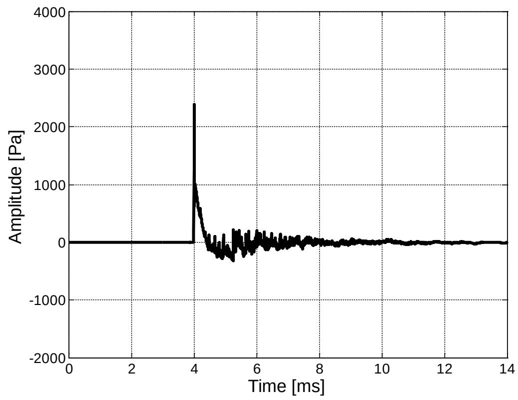

Figure 3: Recording of .308 rifle shot, 3 meters 81° off-axis, no reflections. The ballistic shockwave from the supersonic bullet does not propagate in the direction of this microphone.

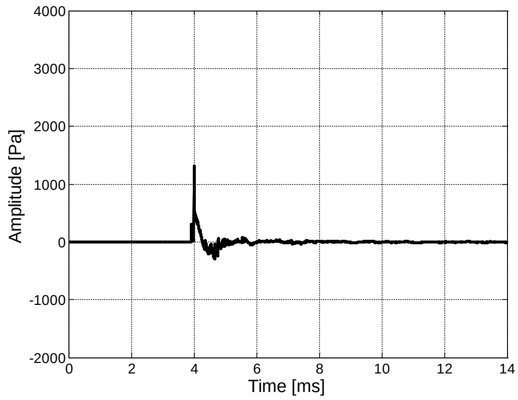

Figure 4: Recording of 9mm handgun shot, 3 meters 81° off-axis, no reflections.

The ammunition used for the rifle was commercial 175 grain Sierra MK, and for the handgun 135 grain Hornady FlexLock +P, used right out of the box. We made no attempt to match the individual parameters of each cartridge.

3.1 .308 rifle shots

The envelope of the ten successive shots from .308 rifle is shown in Figure 5. The envelope depicts the range of instantaneous pressure recorded at each time sample for the ten shots. Each shot has been aligned in the plot at that the peak of the muzzle blast.

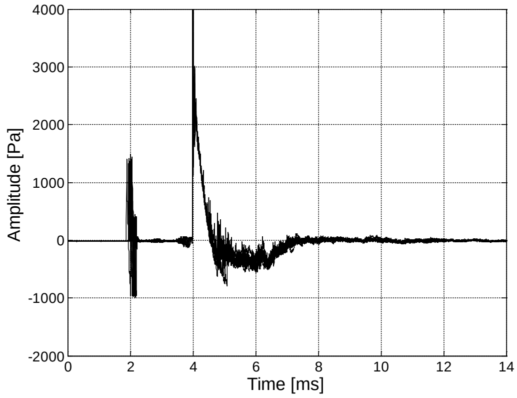

Figure 5: Overlapped plot of ten successive gunshots from the .308 rifle. The shots are similar, but exhibit measurable shot-to-shot differences.

Zooming in on the portion of Fig. 5 that corresponds to the ballistic shockwave, we can examine the relative time-of-arrival of the shockwave for each of the ten shots, as shown in Figure 6. The time difference between the earliest shockwave arrival (shot 10, 1.886 ms) and the latest arrival (shot 3, 2.066 ms), corresponds to 0.18 milliseconds, or 6 centimeters assuming a 338 m/s sound speed at 10°C. We consider that discrepancy to be within the likely shot-to-shot tolerance of the marksman's manual positioning and aiming of the rifle. Another possibility is that the nominal speed of the bullet (2,650 ft/s = 807.8 m/s) may vary from cartridge to cartridge resulting in a difference in time-of-flight for the bullet to the vicinity of the microphone. Future work will seek to understand the expected standard deviation in muzzle velocity and shockwave behavior.

3.1.1 .308 muzzle blast peak pressure

Comparing the on-axis (microphone #1) peak pressure that occurs at the start of the muzzle blast, we see in Figure 7 that for the ten .308 rifle shots the measured peaks are within about 10% of the average peak pressure.

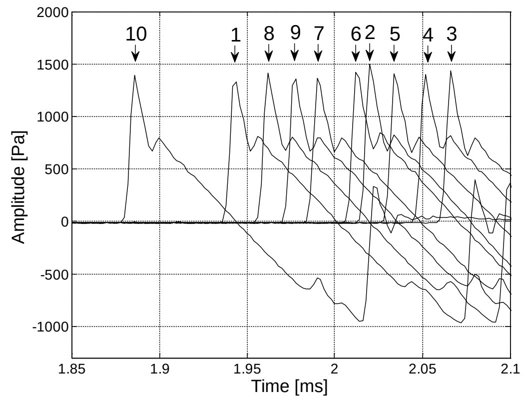

Figure 6: Enlargement of Fig. 5 ballistic shockwave section for ten successive shots from the .308 rifle with time alignment based on the muzzle blast. Numerical labels indicate the order of the ten shots.

Figure 7: Peak pressure for ten successive gunshots from the .308 rifle.

3.2 Glock 19 shots

The envelope of nine shots (1-2, 4-10) from the Glock 19 handgun is shown in Figure 8. The traces show general similarity.

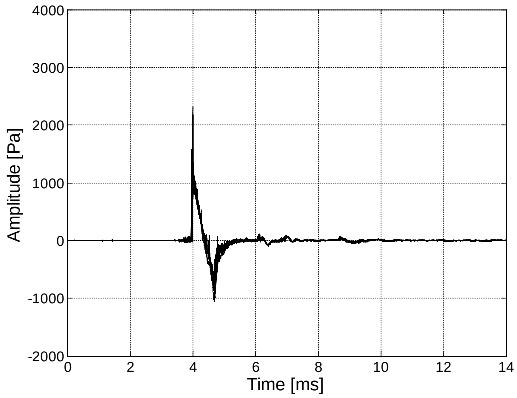

Figure 8: Overlapped plot of nine successive gunshots from the Glock 19 handgun. The shots show visual similarity.

However, shot #3 in the sequence exhibited a secondary strong impulse following the first impulse of the muzzle blast, as shown in Figure 9. The cause of this second impulse is not yet known, although a similar characteristic is found in several of the recordings. Because this recording is from microphone 1 located nearly on-axis with the firearm, one other possibility is that the bullet passed close enough to the microphone to cause an aerodynamic effect.

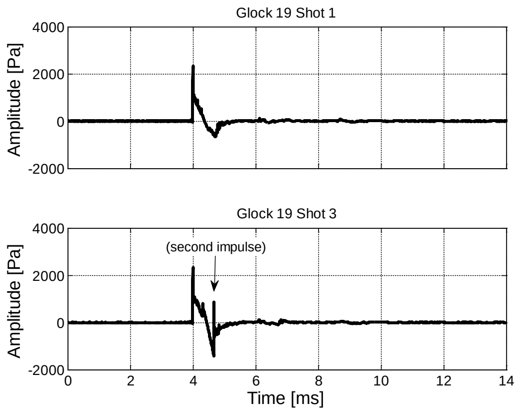

Figure 9: Comparing Shot #1 and Shot #3 from Glock 19 handgun, showing unexpected second impulse.

An enlarged section of the Glock 19 recordings for Shot #3 and Shot #4 is shown in Figure 10. The initial portion of the muzzle blast for these two shots is quite similar, but the tail of Shot #3 occurs sooner and with a larger impulse than of the tail of Shot #4. The explanation for the Shot #3 waveform and the shot-to-shot difference is not yet known.

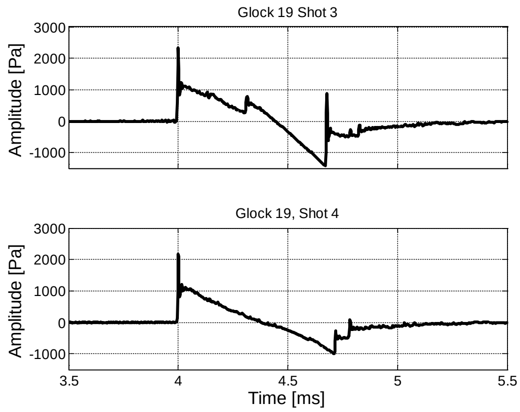

Figure 10: Enlarged section of muzzle blast for Shot #3 and Shot #4, showing the difference in the second portion of the waveform.

3.2.1 *Glock 19 muzzle blast peak pressure*

Comparing the on-axis (microphone #1) peak pressure for the ten shots from the Glock 19 handgun, a greater variability is observed, as shown in Figure 11. The peak pressure variation raises a question from the standpoint of repeatability. Is the variation due to variability in the ammunition, or is it due to a peculiarity of the recording system or the manner in which the test was conducted? The answer to this question is under investigation.

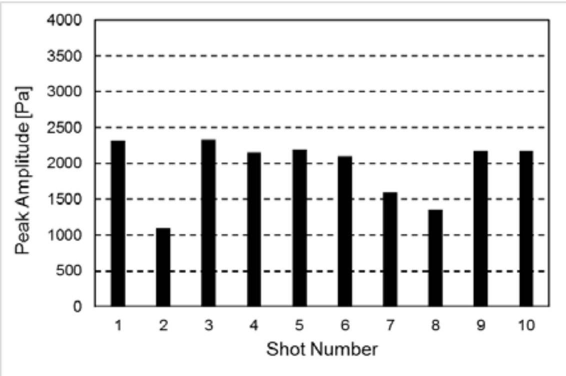

Figure 11: Peak pressure for ten successive gunshots from the Glock 19.

Examining the waveforms for Glock 19 Shot #1 and Shot #2, it is apparent that the abrupt impulse spike observed in nearly every case at the onset of the muzzle blast is not evident for Shot #2, as seen in Figure 12.

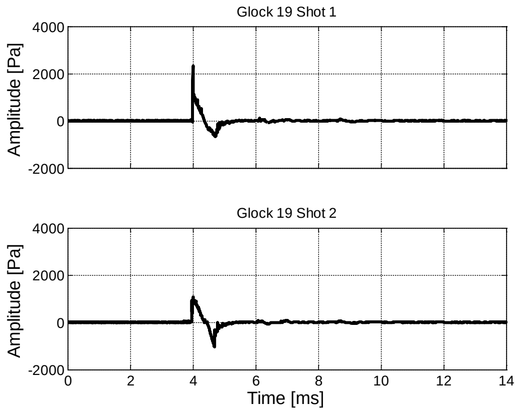

Figure 12: Difference observed between the initial pressure spike for Glock 19 handgun Shot #1 and Shot #2.

Enlarging the time interval at the onset of the muzzle blast for Shot #2 reveals a different pressure profile for that particular shot recording, as shown in Figure 13. The cause of this difference is not known: it could be attributed to the shot itself, or to a discrepancy in the recording system, although this peculiarity in the microphone 1 (on-axis) recording is also observed in the recordings from greater azimuths for Shot #2.

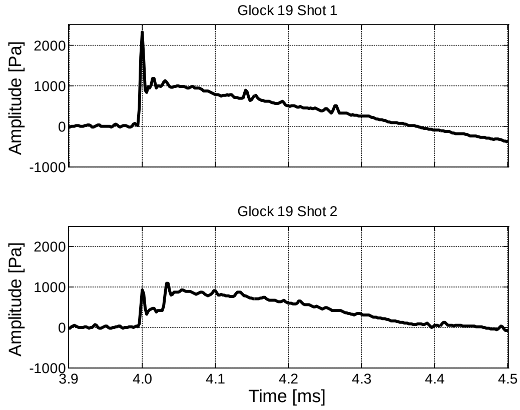

Figure 13: Enlargement of the muzzle blast onset of Fig. 12, showing the waveform difference observed between Shot #1 and Shot #2.

3.2.2 Estimated variability in repositioning hand-held gun between shots

Using the twelve microphone signals and the fact that the data acquisition system samples each channel synchronously, it is possible to observe the time-of-arrival of the muzzle blast at each of the microphones. For example, for the Glock 19 shots the relative delay of the sound arrival can be used to estimate the firearm's position with respect to the microphones under the assumption that the sound propagates at equal speed in all directions. The calculated estimate of the muzzle position can be compared for each of the ten shots, as indicated in Table 1 and Figure 14.

As depicted in Fig. 14, the calculated position of the muzzle varied from one shot to the next over a distance of approximately 10 cm in the X direction (side to side) and 10 cm in the Y direction (forward and backward). The differences are assumed to be caused by the marksman's slight repositioning differences between shots.

4 Azimuthal variation

As has been noted in our prior work, the received muzzle blast waveform varies as a function of azimuth. The angular dependence of the received waveform for the .308 rifle, Shot #1, is shown in

Figure 15, and the plot for Shot #1 of the Glock 19 handgun is shown in Figure 16.

Shot	X origin [cm]	Y origin [cm]
1	15	8
2	16	9
3	15	13
4	14	11
5	13	9
6	16	12
7	11	10
8	14	9
9	18	8
10	17	9

Table 1: Position of the muzzle for ten successive shots of the Glock 19 handgun calculated from relative acoustical delay of sound arrival at the microphones, with respect to the geometric center of the 12 microphone array.

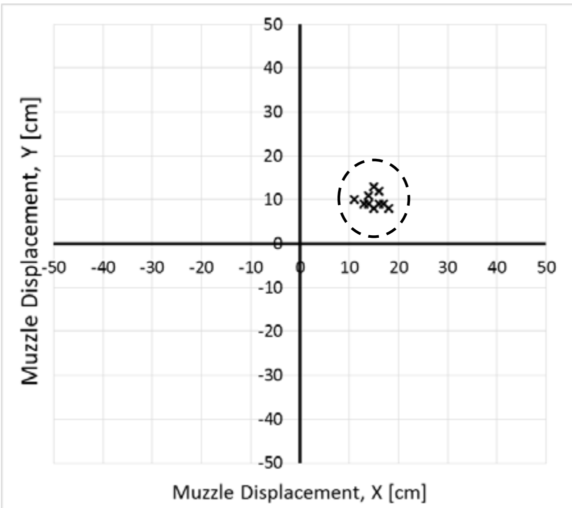

Figure 14: Position of the muzzle for ten successive shots of the Glock 19 handgun calculated from relative acoustical delay of sound arrival at the microphones, with respect to the geometric center of the 12 microphone array.

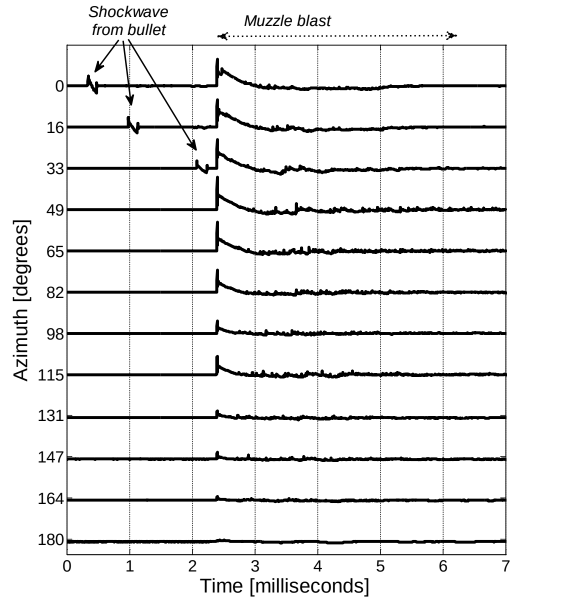

Figure 15: Recordings of a .308 rifle shot as a function of azimuth (0° azimuth is on-axis in front of the barrel, 180° is behind the shooting position).

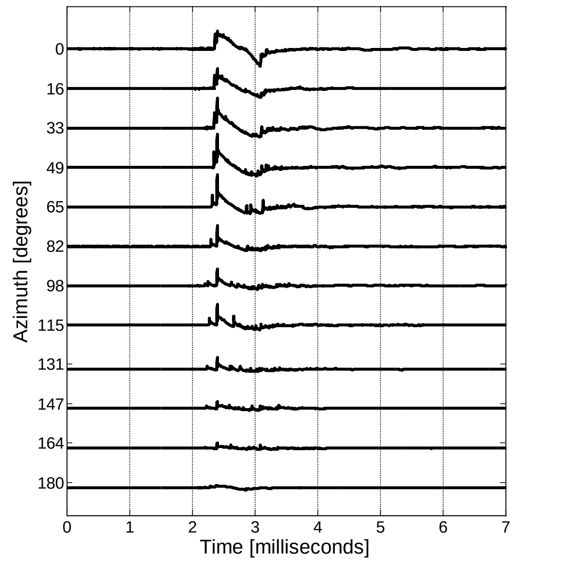

Figure 16: Recordings of a Glock 19 handgun shot as a function of azimuth

5 Future work

As explained in this paper, gaining an understanding of the shot-to-shot variability in gunshot acoustics is potentially relevant to audio forensic analysis. Future recordings with our quasi-anechoic system will involve several changes.

First, we will take steps to measure the weight and physical dimensions of each cartridge, and to measure the muzzle velocity of each bullet, as a way to assess their relationship to the acoustical properties. Second, we will investigate ways to provide a more reliable opportunity for the marksman to reposition the firearm between shots, and also consider the use of an approved mounting fixture to hold the firearm. Finally, we plan to investigate the origin of the fine structure observed in the muzzle blast waveforms and the shot-to-shot variation of this feature to ascertain whether it is a chaotic behavior or a deterministic characteristic of the firearm itself.

6 Conclusions

This paper described our work to record several successive gunshots from a rifle and a handgun under controlled conditions with a quasi-anechoic methodology. The successive shots generally show good shot-to-shot consistency for the muzzle blast, but small variations in waveform details, peak levels, and blast duration are also observed.

The implications for audio forensic analysis remain to be seen, but the results of this study indicate that even under the reasonably ideal circumstances of these tests, the shot-to-shot differences are noticeable. As noted here and also in our prior work, there is generally a significant waveform and sound level difference attributable to the azimuth angle between the barrel of the firearm and the observation position. This directionality can cause apparent shot-to-shot variations if the direction the firearm is pointing changes from one shot to the next.

7 Acknowledgements

This research work is supported by National Institute of Justice grant 2014-DN-BX-K034. We thank Prof. Steven Shaw, Montana State University, and Lt. Col. Angelo Borzino, Military Engineering Institute, Rio de Janeiro, Brazil, for their expert assistance with the gunshot recordings and interpretation.

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