DIRECTIONAL ASPECTS OF FORENSIC GUNSHOT RECORDINGS

ROBERT C. MAHER AND STEVEN R. SHAW

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

Crime scene forensic evidence may include audio gunshot recordings obtained from some known or assumed location with respect to the shooting position. The acoustic evidence of the gunshot depends significantly upon the relative orientation of the firearm's barrel and the recording microphone due to the inherent directional characteristics of the gun, the microphone, and the acoustical characteristics of the surrounding environment. This paper describes an experiment involving the directional characteristics of several types of firearms.

INTRODUCTION

Gunshot acoustical evidence can play an important role in audio forensic reconstruction and analysis projects involving firearms [1-5]. The sound of the gunshot may be captured by an audio surveillance system, a telephone conversation, or inadvertently by a journalist or member of the public making an audio-visual recording. Even in cases without a physical recording, the forensic examiner may be asked to assess subjective questions such as the ability of a listener to identify a particular type of firearm based on its sound, or to discriminate between the sounds of two or more different firearm types. The examiner may also be asked to assess the likelihood that a gunshot produced at a specified location would be audible by a witness located at some other location.

In general, audio forensic assessments of this sort are difficult to answer unequivocally without having a thorough understanding of the firearm type and the spatial position and orientation of the firearm with respect to the witness and/or the recording microphone. The orientation of the firearm can affect the received sound level, and therefore the characteristics of the recorded audio signal [1, 2, 5, 7].

To help understand the effects of firearm type and directionality, an experiment was conducted to examine the received sound level as a function of azimuth for shots from ten different firearms. This paper presents a preliminary analysis of the results.

Conventional firearms operate by channelling the rapidly expanding gases produced by the confined combustion of gunpowder to accelerate a bullet through the gun barrel. The combustion gases expand rapidly behind the bullet and emerge from the muzzle of the firearm, producing an impulsive, chaotic noise known as the muzzle blast. The muzzle blast sound typically lasts only a few milliseconds. The peak sound pressure level (SPL) associated with the muzzle blast can exceed 150dB re 20 μPa in the vicinity of the firearm [6, 7].

The paper is organized as follows. The experimental conditions and specific firearms tested are described first. Next, we provide a summary of the essential results and findings. Finally, we give several conclusions and recommendations for future work.

1 EXPERIMENTAL PROCEDURE

The muzzle blast has directional characteristics that depend upon the design of the firearm and the details of the ammunition used. The general directional behavior of several firearm types is the focus of this experiment.

Figure 1: Example test configuration for firearm acoustical tests. The microphones are repositioned between shots to cover the 180 degree azimuth range.

1.1 Test conditions

An example of the test configuration is shown in Figure 1. The experiment consisted of a series of gunshots with microphones located 3 meters radially from the muzzle over a 180° range of azimuth, with zero azimuth being nearly on-axis in front of the muzzle, 90° being perpendicular to the axis of the barrel, and 180° being behind the shooter. The muzzle of the firearm was oriented horizontally when fired at an elevation of approximately 3 m above the ground. The skilled marksman was instructed to avoid shooting the microphone, so the zero azimuth position is actually a few degrees off-axis.

A two-channel recording was obtained for each shot and azimuth position using a matched pair of professional omnidirectional electret condenser microphones (DPA 4003), a corresponding high voltage (130 V) preamplifier (HMA 5000), and stereo audio recorder operating with 24-bit resolution and a 44.1 kHz sample rate per channel (TASCAM HD-P2). The two microphones were spaced 48 cm apart on a stand mounted approximately 3 m above the grassy, frozen surface of the test range. This configuration was chosen to ensure that the ground reflection was delayed by approximately 10 ms compared to the direct sound path from the firearm to the microphones. The ambient air temperature was 30° F (-1 C), indicating a local speed of sound of 330.6 m/s.

Prior to the actual firearm test sequence the microphones and the recording system were carefully calibrated and tested to ensure that the recording chain could accommodate the very high instantaneous sound pressure levels associated with the gunshots without clipping. A Bruel & Kjaer Type 4231 microphone calibrator with DPA 4003 microphone adapter was used to record a 94dB calibration tone for each microphone channel at the start of the experiment.

Each investigator wore suitable hearing protection throughout the testing. The test sequence for each firearm consisted of the following steps. First, the range was checked for safety, and the investigators prepared the firearm and performed the recording system calibration steps. Next, the microphones were positioned at the first azimuth position, resulting in azimuths of approximately 0° (on axis) for the channel 1 microphone and 9° for the channel 2 microphone, and the recorder was started. The marksman positioned himself at the proper altitude and orientation with respect to the firing line, aimed at the designated target area, and performed the shot. The microphones were repositioned to the second azimuth position, giving azimuths of approximately 49.5° for channel 1 and 40.5° for channel 2, and another shot was made. The process was repeated for ~90° , ~135°, and finally ~180°. The process was repeated for each of the ten firearms tested.

1.2 Firearms tested

The ten firearms used in the experiment included three rifles, a shotgun, and six handguns. The firearms were selected to be representative of the guns likely to be encountered in U.S. forensic audio investigations. The load information is provided for reference only: serious injury can occur from improper loads.

1. ***308 Winchester rifle***
   24" Krieger barreled Surgeon action in an Accuracy International Chassis. *Load*: 168 gr Sierra Matchking, 43.5 gr Varget, Fed 210 GMM Primer, Lapua brass, ~2630 fps.
2. ***223 Remington rifle***
   STAG 15, carbine configuration, 18" barrel. *Load*: Black Hills Ammunition, 55gr FMJ (full metal jacket).
3. ***12 gauge shotgun***
   Remington 870 "Home Defense", 18" barrel. *Load*: Federal Premium 2.75" 00-buck.
4. ***22 long rifle***
   CZ-452, 20" barrel. *Load*: Remington/Eley Target Rifle.
5. ***45 ACP handgun***
   Colt Gunsite Pistol, 5" 1911. *Load*: Remington UMC 230 gr FMJ.
6. ***10 mm auto handgun***
   Glock 20, 4.6" match barrel. *Load*: Double-tap 180 gr JHP (jacketed hollow point).
7. ***40 S+W handgun***
   Browning High-Power. *Load*: 165 gr Corbon JHP.
8. ***357 Magnum handgun***
   Ruger SP-101, 3 inch barrel. *Load*: Federal 158 gr JSP (jacketed soft point), load #AE357A.
9. ***9x19mm handgun***
   Glock 19, 4" barrel. *Load*: 124 gr Speer GDHP (gold dot hollow point), 7.7 gr BlueDot, Starline case, Remington 1.5 primer.
10. ***38 Special handgun***
    Smith+Wesson 442. *Load*: Winchester Super-X 38 Special +P 125gr JHP, load X38S8HP.

2 EXPERIMENTAL RESULTS

The experimental data consists of audio recordings from ten different azimuths for each of the ten firearms. The gunshot data can be analyzed in several different ways depending upon the needs of a particular audio forensic investigation.

2.1 Sound level as a function of azimuth

The first comparison treats the mean sound pressure level for each firearm as a function of azimuth. Each gunshot audio file was processed with computer software to identify the onset of the muzzle blast. A 400 sample (9 ms) window beginning 50 samples prior to the detected muzzle blast was used to calculate the RMS sound pressure for each shot, with the 94dB recorded calibration tone as the reference. The time window was selected both to avoid onset accuracy errors and to eliminate the subsequent arrival of ground reflections.

2.1.1 Directional characteristics

The unweighted SPL, 20 $\log_{10} (P_{RMS}/P_{ref})$, for the large rifle and shotgun tests is shown in Fig. 2 (P_{ref} = 20 μPa). All three firearms shown in this figure produce on-axis levels near 145 dB, declining by approximately 15 dB for azimuths behind the shooter. The 12 gauge shotgun exhibits a somewhat more directional characteristic than the 308 and 223 rifles.

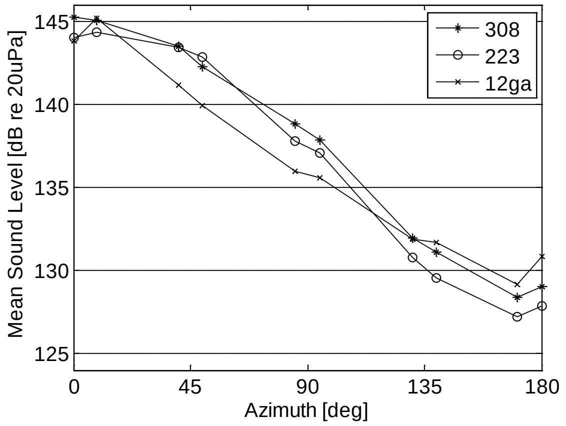

Figure 2: Comparison of unweighted mean SPL for the 308 and 223 rifles and the 12 gauge shotgun, as a function of horizontal azimuth.

The data appear to show an interesting anomaly near the 180° azimuth angle, because the measured level at 171° is lower than the 180° position directly behind the firearm. We believe this result is due to the acoustical shadowing of the shooter: the firearms were held in the right hand or at the right shoulder of this right-handed marksman (see Fig. 1).

The corresponding directional level comparison for four of the handguns is shown in Fig. 3. The on-axis level for the 357 handgun is comparable to the 223 rifle and 12 gauge shotgun, and approximately 4 dB higher than for the 9mm, 10mm, and 40 handguns. Of the four guns compared in Fig. 2, the 10mm shows a roll-off of only 12 dB with increasing azimuth, while the 357, 9mm, and 40 show a difference of 15 dB, which is similar to the azimuth dependence of the rifle shots.

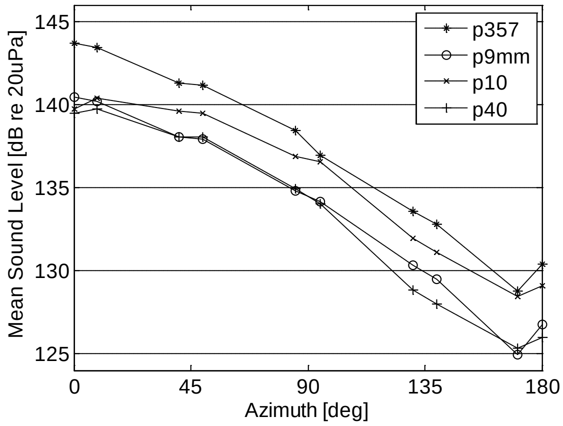

Figure 3: Comparison of mean SPL for four handguns: 357, 9mm, 10mm, and 40, as a function of horizontal azimuth

Figure 4 shows the SPL results and azimuth dependence of the 357 (repeated from Fig. 3 for comparison), 38, and 45 handguns. The 38 and 45 produce a relatively low on-axis sound level, and a roll-off of 10 dB or less between zero and 180° azimuth.

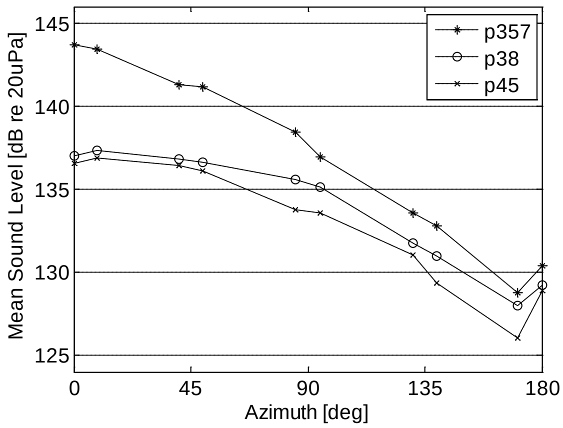

Figure 4: Comparison of mean SPL for three handguns: 357, 38, and 45, as a function of horizontal azimuth.

Figure 5 presents a comparison of level and azimuth dependence for the 22 rifle compared to the 308 rifle and the 357 and 45 pistols. The 22 is significantly quieter at all azimuths than any of the other firearms tested. The 22 is also highly directional, showing a roll-off of nearly 30 dB between the on-axis position and the 180° azimuth position.

2.1.2 Sound level comparison

The on-axis muzzle blast sound level for the ten firearms ranged from just over 145 dB unweighted SPL for the 308 rifle to just under 120 dB for the 22 rifle, a span of about 25 dB. The overall on-axis mean SPL information for the ten firearms is summarized in Figure 6.

The minimum off-axis (typically near 180° azimuth) sound level for the ten firearms ranged from 129 dB for the 12 gauge shotgun to approximately 90 dB for the 22 rifle, a span of nearly 40 dB. The minimum levels for the ten firearms are given in Figure 7. Note that the highest sound level produced by the 22 rifle used in this experiment is actually lower than the minimum sound level produced by any of the nine other firearms tested.

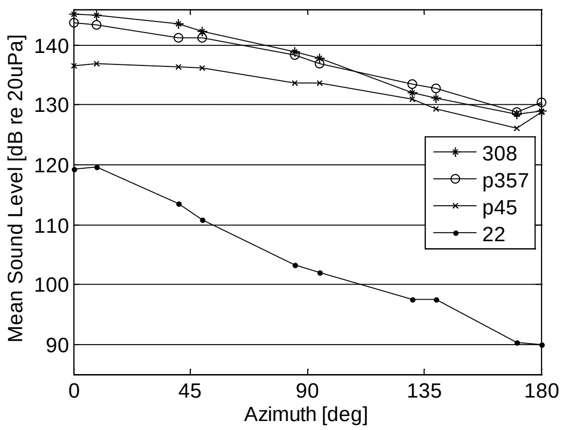

Figure 5: Comparison of mean sound pressure level for the 308 rifle, 357 and 45 pistols, and the 22 rifle, as a function of horizontal azimuth.

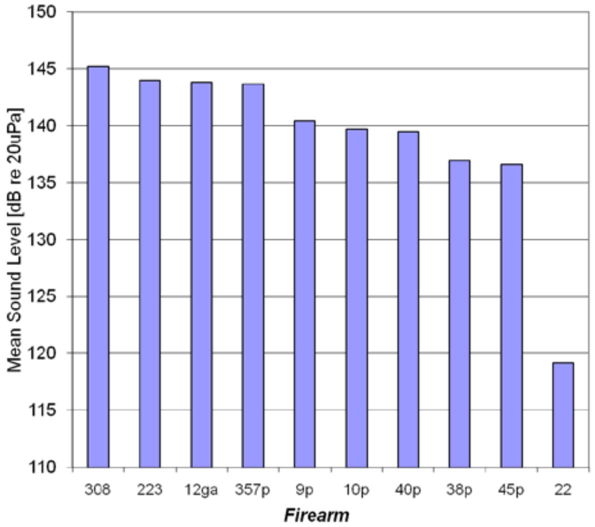

Figure 6: On-axis (max) mean SPL for ten firearms.

2.2 Waveform comparison

Some forensic audio projects entail waveform and timing analysis. The second set of comparisons treats the variation in the time waveform for the firearm as a function of azimuth.

2.2.1 Directional characteristics

Figure 8 contains the set of gunshot recordings from the ten azimuth positions for the 308 rifle. The muzzle blast for each azimuth is the disturbance at the center of the plot. Note that the recordings for the 0° and 9° positions contain a shockwave signature several milliseconds before the arrival of the muzzle blast due to the passage of the supersonic bullet [3, 4, 5]. The wider azimuths do not show the bullet's shockwave, as the shockwave cone trailing the bullet propagates outward and forward, and therefore does not intersect the wider microphone positions. For example, the 308 projectile exits the muzzle at approximately 800 m/s, or 2.4 Mach for the 30° F ambient temperature. The corresponding Mach Angle is just 24.4°.

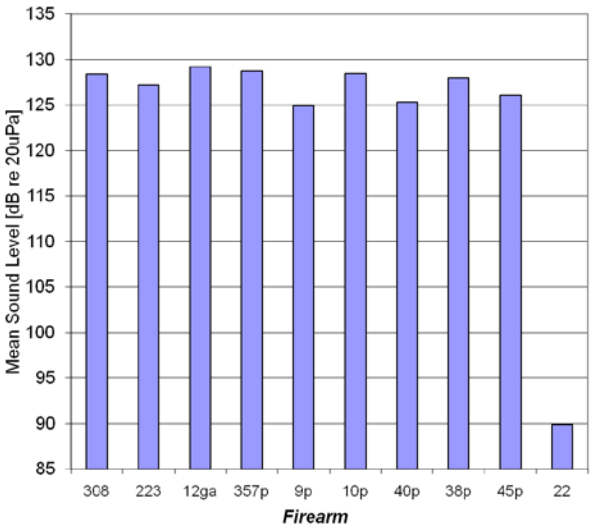

Figure 7: Minimum mean sound pressure level (off-axis) for ten firearms.

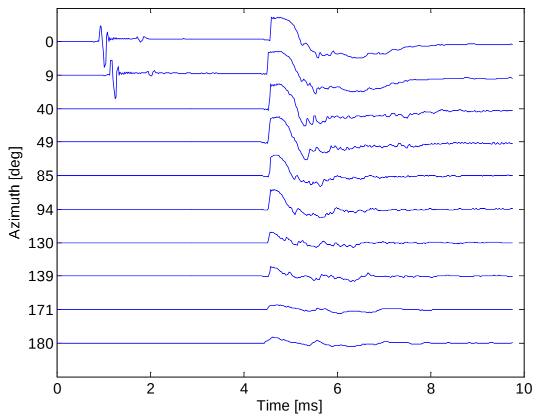

Figure 8: Gunshot waveforms for 308 rifle as a function of azimuth. Each trace is the pressure waveform corresponding to the indicated azimuth position.

Figure 9 shows the waveforms as a function of azimuth for the 357 handgun. Note that the 357 exhibits an interesting double-bump waveshape for the side azimuths between 85° and 139°. The 357 is a revolver, so its acoustical emanations may come from both the muzzle and from the gap between the cylinder and the stationary barrel, potentially causing time differences or interference phenomena.

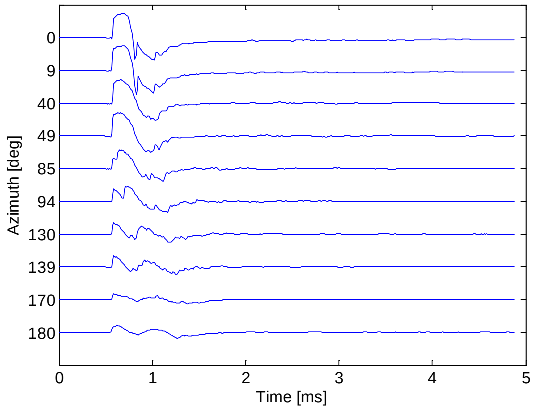

Figure 9: Gunshot waveforms (amplitude vs. time) for 357 handgun as a function of azimuth.

The recorded waveforms for the 38 handgun are shown in Figure 10. The 38 is also a revolver, but is a much less powerful handgun than the 357, and shows a relatively consistent waveshape over a wider azimuth range.

As a final example, the waveforms of the 40 handgun are given in Figure 11. The gunshot waveform for this firearm shows a distinctive waveshape for the nearly on-axis recordings at 0° and 9°, compared to the wider azimuths.

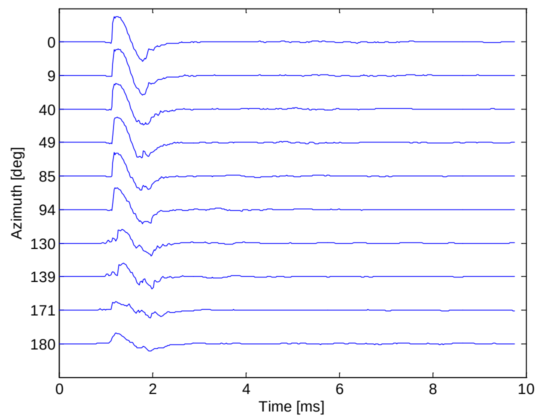

Figure 10: Gunshot waveforms (amplitude vs. time) for 38 handgun as a function of azimuth.

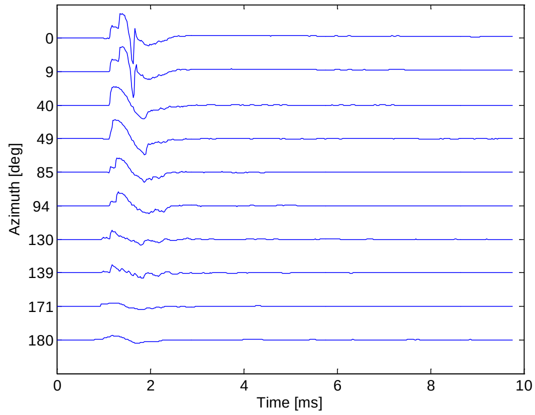

Figure 11: Gunshot waveforms (amplitude vs. time) for 40 handgun as a function of azimuth.

2.2.2 *On-axis waveform comparison*

The on-axis waveforms for the ten firearms are shown in Figure 12 with the same amplitude scale for each waveform. The projectile's shock wave for the 308 and 223 examples is not shown. For visual examination, the gunshot waveform features show noticeably different and distinct waveshapes.

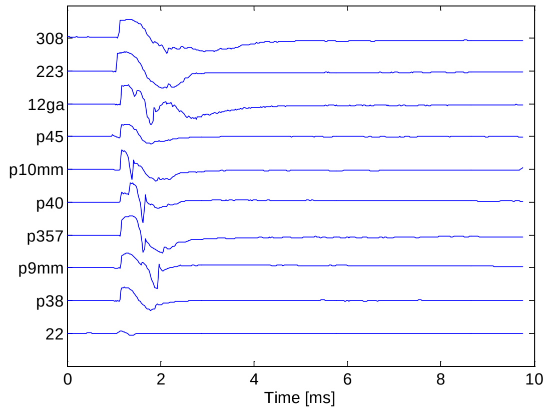

Figure 12: Gunshot waveform (amplitude vs. time) comparison for the ten firearms; on-axis position.

3 DISCUSSION

The results of this experiment have several implications for forensic gunshot acoustic analysis.

As would be expected, the general trend in sound pressure level is directly related to the calibre and load of the ammunition: larger gunpowder loads and calibre correspond to higher SPL readings. The highest mean SPL readings at 3 m from the muzzle exceed 145 dB re 20 μPa, and would undoubtedly result in recording system clipping and non-linear distortion for most conventional audio recording systems.

The variation in SPL for the various firearms could provide a way to discriminate different gunshots occurring in the same vicinity. The substantial difference in level between the 357 handgun (144 dB SPL on-axis) and the 38 or 45 handguns (137 dB SPL on-axis) appears to be sufficient for an examiner to differentiate reliably these shots in an audio recording. The level differences between the various firearms may also be sufficient for an experienced listener to make a judgement about differing loudness if shots are witnessed from more than one firearm in close time sequence. However, the experiment reported in this paper does not treat the issue of human audibility and perceived loudness, so further work will be necessary to investigate the subjective importance of the gunshot SPL comparisons described in Section 2.

The noticeable visual differences between the on-axis waveforms for the various firearms tested in this experiment make it tempting to conclude that the firearm type can be identified from forensic audio recordings. Although the data from this experiment appears encouraging, it is important to keep in mind that crime scene audio recordings are seldom available with the relatively pristine quality of the gunshot observations made in this controlled study.

Finally, it is important for audio forensic examiners to recognize that the difference in level and waveform details between on-axis and off-axis recordings *of the same firearm* are often significantly greater than the difference between two firearm types at the same azimuth. This can have an important effect upon deducing the firearm type from a recording, especially if the orientation of the firearm with respect to the microphone is not known from some other source of information.

4 CONCLUSIONS

This paper describes several acoustical observations for gunshot recordings that may be relevant for forensic audio interpretation. The observations were made deliberately in an acoustically simple environment so that the direct sound of the muzzle blast could be isolated from multipath reflections and reverberation. The recordings were made with suitable distance and attenuation to prevent obvious signal clipping at the microphone or in the recording system, but it is important to note that this investigation was limited to the audio bandwidth (to 20 kHz), so ultrasonic features and other shot details are not examined. Nevertheless, the audio bandwidth is relevant because it is typical of most audio forensic crime scene evidence.

Forensic gunshot audio obtained for surveillance purposes or via telephone recordings will typically contain acoustic reflections, background noise, clipping, and other interfering signal characteristics that may complicate the interpretation of the forensic audio examiner. Therefore, the audio examiner is advised to obtain as much information about the spatial relationship between the firearm and the microphone, the characteristics of the recording system, the acoustical surroundings of the location, and the circumstances surrounding the recording itself, before drawing conclusions from recorded gunshot evidence.

5 ACKNOWLEDGEMENT

This experiment was conducted using the facilities of the Montana State University Red Bluff Research Ranch, Mr. Pete Olind, ranch manager. The assistance by the ranch staff is gratefully acknowledged.

REFERENCES

[1] 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.

[2] 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.

[3] Maher, R.C. "Modeling and signal processing of acoustic gunshot recordings," Proc. IEEE Signal Processing Society 12th DSP Workshop, Jackson Lake, WY, September 2006.

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

[5] Maher, R.C. and Shaw, S.R., "Deciphering gunshot recordings," Proc. Audio Engineering Society 33rd Conference, Audio Forensics—Theory and Practice, Denver, CO, June 2008.

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

[7] NORDTEST Method, "Shooting ranges: prediction of noise," NT ACOU 099, edition 2, Espoo, Finland, November 2002.