Audio Engineering Society

Convention Paper 9471

Presented at the 139th Convention
2015 October 29-November 1 New York, USA

Advancing Forensic Analysis of Gunshot Acoustics

Robert C. Maher and Tushar Kanti Routh

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

ABSTRACT

This paper describes our current work to create the apparatus and methodology for scientific and repeatable collection of firearm acoustical properties, including the important direction-dependence of each firearm's sound field. Gunshot acoustical data is collected for a wide range of firearms using an elevated shooting platform and an elevated spatial array of microphones to allow echo-free directional recordings of each firearm's muzzle blast. The results of this proposed methodology include 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. INTRODUCTION

Gunshot acoustics is a specialization within the audio forensics field [1]. Forensic gunshot acoustical analysis typically involves a recording obtained from a law enforcement call/dispatch center or perhaps from an electronic newsgathering or surveillance system. The acoustic evidence obtained from the recording can help support or refute witness accounts about a crime scene, such as the order of events, the location and orientation of the firearms, and the number of gunshots.

For at least the past 20 years in the United States the use of in-car Mobile Video Recorder (MVR) dashboard-mounted video camera systems has become widespread for police cruisers, and audio/video recordings from these systems have been used as evidence in numerous investigations and court proceedings. More recently, inexpensive and lightweight digital voice recorders and miniature personal digital video camera systems have become popular for routine law enforcement and surveillance use. In some jurisdictions the use of these recording systems is required by agency policy, and in other cases an individual officer may choose to carry a personal recording system to document objectively his or her actions as a way to protect against unfounded allegations of misconduct. Thus, the use of these recording systems is becoming ubiquitous [2].

Criminal and civil investigations increasingly draw upon audio forensic evidence and interpretation. 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. Audio forensic evidence also frequently comes from emergency dispatch center recordings of telephone calls and land-mobile radio communications, as well as recordings from journalists and even bystanders using mobile phones to make ad hoc video recordings of an incident while it happens.

Therefore, it is reasonable to expect an increasing number of law enforcement investigations will include audio forensic evidence, and further to expect that an increasing number of cases involving gunshot incidents will be captured in audio recordings. Thus, it is now critical for forensic examiners to understand the strengths and weaknesses of the audio recording systems used in mobile audio recorders and mobile phones, particularly the miniature digital voice recorders carried by many law enforcement officers, in the context of gunshot interpretation [3, 4].

This paper describes our current research effort to describe and to understand the fundamental features of gunshot acoustics applied to audio forensic investigations.

1.1. Research issues for gunshot acoustics

While the availability of additional acoustic evidence of firearm incidents can only be a positive development for the U.S. justice system, two major issues must be addressed. First, the acoustical characteristics of gunshots are currently little understood in an objective sense, and often subject to unscientific physical misunderstandings and subjective interpretation that is no longer appropriate in forensic science. Second, the response of common mobile phones and personal audio recorders to intense acoustical sounds such as gunshots has not been studied in any systematic manner, and this lack of knowledge seriously limits the ability of an audio forensic examiner to use recorded acoustic evidence to draw reliable conclusions. Common personal audio recorders are designed to capture human speech conversations, and the forensic impact of speech-optimized processing and digital encoding algorithms on unanticipated sounds such as gunshots is not known.

Therefore, the challenge for audio forensic examinations involving gunshot evidence obtained from speech-oriented audio recording devices is to determine what aspects of the waveform and timing information is likely to be reliable for interpretation.

1.2. Gunshot research goals

Our current research underway involves three goals.

- Increase the audio forensic knowledge base via objective measurement of firearm acoustics under controlled, repeatable conditions.
- Understand the limitations on forensic interpretation of gunshot acoustical evidence obtained from speech-channel recording devices, such as mobile phones, land-mobile radio, personal audio recorders, and audio data collected by emergency call center and dispatch center recording systems.
- Develop a preliminary system for acoustical simulation of gunshots recorded in acoustically complex surroundings via ray-tracing (high frequencies) and wave-based (low frequency) models.

This paper reports on our progress toward the first goal, which is to develop and demonstrate a methodology for objective, reliable, and repeatable measurement of gunshot acoustics for a firearm under test. Because this work is currently underway, this paper serves as a status report of our progress.

2. GUNSHOT AUDIO FORENSIC INFORMATION

Assessing and evaluating acoustic gunshot detection systems requires a thorough understanding of the characteristics of gunshot sounds and the significance of sound wave reflection, absorption, and diffraction from the ground, buildings, and other nearby objects [5-9].

2.1. Muzzle blast

A conventional firearm uses confined combustion of gunpowder to propel the bullet out of the gun barrel. The sound of the rapid combustion is emitted from the gun in all directions, but the majority of the acoustic energy is expelled in the direction the gun barrel is pointing [9]. The nonlinear shock wave and related sound energy emanating from the barrel is referred to as the *muzzle blast*, and typically lasts for less than 3 milliseconds. The muzzle blast acoustic wave propagates through the air at the speed of sound (e.g., 343 m/s at 20°C), and is partially reflected, absorbed, and diffracted by the surrounding ground surface and other physical obstacles. The muzzle blast is also subject to refraction by air temperature and wind gradients, spherical spreading, and atmospheric absorption. In nearly all real-word situations the received acoustic signal will also exhibit propagation effects, multi-path reflections, and reverberation.

2.2. Supersonic Projectile

In addition to the muzzle blast, another significant source of acoustic gunshot information is present if the bullet travels at supersonic speed [6, 10, 11]. The supersonic projectile's passage through the air launches an acoustic *shock wave* propagating outward from the bullet's path. The shock wave expands in three-dimensions as a shock wave cone behind the bullet, with the wave front (cone face) propagating outward at the speed of sound. The shock wave cone trailing the bullet has an inner angle, $\Theta_M = \arcsin(1/M)$, where $M = V/c$ is the *Mach Number* (V is the bullet's speed, and c is the local speed of sound). Θ_M is referred to as the *Mach Angle*. The geometry is shown in Figure 1.

If the bullet is traveling substantially faster than the speed of sound, the Mach Angle is small and the shock wave propagates nearly perpendicularly to the bullet's trajectory. A bullet traveling only slightly faster than the speed of sound has a Mach Angle approaching 90°, meaning that the shock wave is propagating nearly parallel to the bullet's path. Moreover, as the bullet slows along is path due to friction with the air, the corresponding Mach Angle widens down range.

2.3. Directionality of gunshots

Directional characteristics are very important in understanding the behavior of gunshot sounds, although this aspect has often been neglected in audio forensic gunshot analysis [9, 12].

Gunshot acoustical propagation is sometimes modeled as a point source impulse emanating sound spherically. This is an appealing notion because it would allow simulating a gunshot by convolving a single recorded gunshot waveform with the acoustical impulse response of the space in which the shot occurred. However, the directional acoustical characteristics of common firearms must be included if the forensic audio examiner expects to compare sound propagation modeling with actual forensic recordings [13].

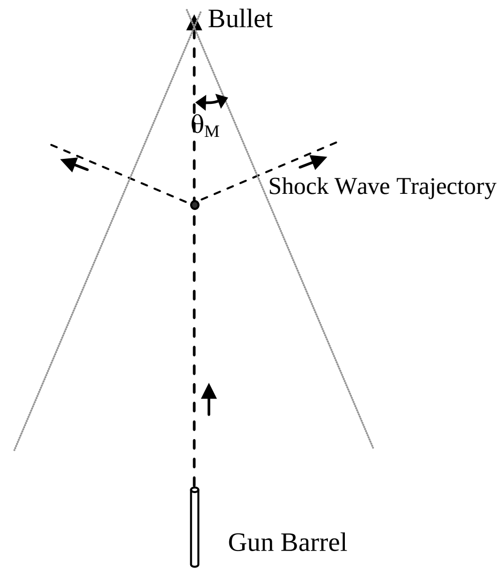

Figure 1: Shock wave geometry for a supersonic projectile traveling with speed V > speed of sound, c. The Mach Angle Θ_M is small for (V/c)»1, and close to 90° for (V/c)≈1.

Many firearms exhibit a broadband sound level difference of ~20 dB SPL between the level on-axis with the gun barrel and the same shot observed directly behind the barrel [9, 12]. Similarly, the acoustic wave shape of the gunshot changes markedly between the signal obtained on-axis and the signal observed at other off-axis azimuths. As we noted in one of our published studies [9]:

> "…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."

Therefore, we assert that a forensic audio examiner should not attempt to ascertain the likely model of the firearm that produced the signature observed in an evidentiary audio recording without careful measurement and documentation of a representative sample of firearm types at the full range of azimuths.

2.4. Reflections and reverberation

Recording an impulsive sound source in the natural environment includes the *direct sound* from the source traveling through the air directly to the microphone position, *early reflections* of the sound that appear as discrete reflections off the ground, nearby surfaces, and other obstacles, and *reverberation* of the sound that comprises overlapping sound reflections arriving at the microphone from more distant surfaces and multiple-order reflections [14]. The early reflections and the reverberation depend upon the acoustical environment where the recording is made and the spacing and relative geometry of the source and microphone, and therefore a recorded gunshot signal will differ from one recording location to another. This inevitable mixture of direct sound and the overlapping sound due to the acoustic reflections makes it difficult to compare recordings of the same firearm made at different locations and with different geometric orientations.

Figure 2a-c shows three gunshot recordings from a single firearm (.308 rifle) but with different geometry of gun and microphone. The bullet's shock wave and ground reflection, and the muzzle blast and its ground reflection, are consistently present but with different timing and amplitude characteristics.

It is clear that even in a relatively simple acoustical situation the recorded gunshot waveform is rather complicated with overlapping signals and reflections. If reflections from walls, berms, vehicles, and other nearby obstacles are included—as would be the case for typical gunshots found in audio forensic evidence—the waveform is significantly more cluttered with the reflected and reverberant sound energy.

2.5. Gunshot acoustical characterization

Obtaining reference-quality gunshot recordings requires careful consideration of the geometry and acoustical physics of the testing configuration. Ideally the recording system is designed to capture only the direct sound of the firearm without reflections and reverberation (anechoic, meaning *no echo*), so that the reference firearm recording is independent of the measurement environment.

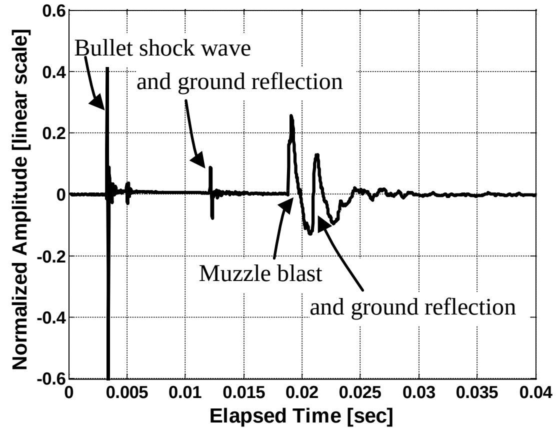

Figure 2a: .308 rifle fired while oriented toward the recording microphone

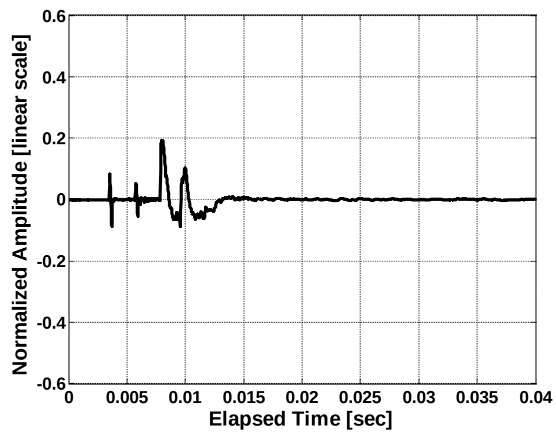

Figure 2b: .308 rifle fired while oriented 45 degrees from the recording microphone

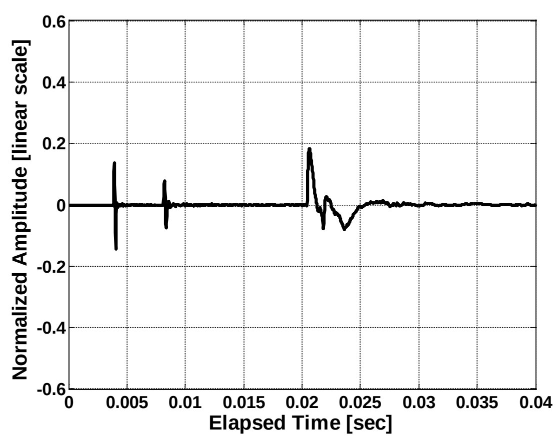

Figure 2c: .308 rifle fired while oriented toward the recording microphone at a greater distance

The peak sound pressure level in the vicinity of the firearm can be over 170 dB re 20 µPa, and the pressure rise-times are extremely short, so obtaining high dynamic range acoustical recordings requires a microphone and preamplifier system appropriate for this unusually intense and abrupt type of sound [7].

Furthermore, because the sound pattern emanating from the firearm is directional, the sound field must be measured at multiple azimuth angles with respect to the firearm's barrel. It may also be possible that some firearms have a cylindrically asymmetrical sound level variation as a function of both azimuth and elevation, so a means to capture the sound pattern in all directions may be necessary. Finally, it is desirable to have time-synchronous recordings simultaneously at multiple angles so that the gunshot acoustical wavefront is properly captured in the test recordings.

3. PROPOSED GUNSHOT RECORDING SYSTEM AND METHODOLOGY

For scientific analysis of gunshot characteristics, the solution to this issue is to arrange the recording system in such a way that the direct sound can be separated from the early reflections and reverberation. One possibility is to make the recordings in an anechoic chamber. This would involve a large, specially designed room fitted with wall treatments that do not reflect sound (nearly perfect sound absorption). Indoor anechoic facilities that are suitable for high intensity impulsive sounds such as gunshots are expensive to build and require special precautions for firearm use that are often unwieldy.

Instead, our proposed approach is to use an elevated shooting platform and microphone rig at a suitable outdoor shooting range, or possibly in an appropriate very large interior space approved for firearm discharge. This approach does not eliminate acoustical reflections and reverberation, but because sound travels 1 meter in approximately 3 milliseconds, by moving the firearm and microphones farther from the reflecting surfaces the arrival of the first reflections will be delayed compared to the direct sound arrival. Choosing the spacing between the firearm and the microphone to be several meters shorter than the acoustical path from the firearm to the first reflecting surface to the microphone, the arrival of the reflected sound occurs 10 or more milliseconds after the direct sound arrival, and this delay is sufficient for the gunshot's entire direct sound to have already passed by. The subsequent reflect sound arrival can be ignored (time gated) in the gunshot recording. The basic quasi-anechoic configuration is shown in Figure 3.

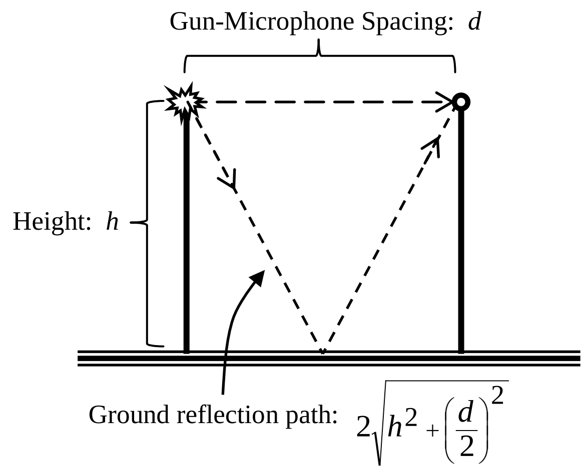

Figure 3: Quasi-anechoic recording using elevated shooting and microphone positions sufficient to delay reflected sound arrival until after the direct sound of the gunshot has been completed.

The direct sound of the gunshot propagates to the recording microphone over distance d, while the first reflection (ground) covers the greater down and up distance. Thus, with speed of sound c, the time-of-arrival difference between the direct sound and the first reflection is the relative distance divided by the speed.

$$T_{diff} = \left(\frac{1}{c}\right)\cdot\left[2\sqrt{h^2 + \left(\frac{d}{2}\right)^2} - d\right]. \quad (1)$$

For example, with $h = d = 3$ meters and speed of sound c=343 meters/second, T_{diff} = 10.8 milliseconds.

3.1. Prior demonstration experiment

In 2010 we conducted a preliminary experiment to demonstrate the feasibility and utility of this procedure for making recordings of the directional acoustical characteristics of several firearms [9]. In that prior demonstration the marksman discharged the firearm from the raised position of a ladder, and the recording microphones was also mounted on an elevated stand. The marksman fired repeatedly at a distant fixed target while the microphones were moved to successively greater azimuth angles between shots. This multiple shot procedure demonstrates the feasibility of directional sound capture, but obviously does not allow time-synchronous (simultaneous) recording at all azimuths.

The demonstration recordings were made using professional omnidirectional electret condenser microphones (DPA 4003) with a corresponding high voltage (130 V) preamplifier (HMA 5000), sampled at 44.1 kHz per channel (TASCAM HD-P2). The DPA system was capable of a maximum 154 dB SPL peak sound level before clipping, and in several cases the gunshot waveform exceeded this level even at a distance of 3 meters.

3.2. Proposed gunshot recording configuration

To accomplish the requirements for quasi-anechoic and time-synchronous recording, a new test rig has been designed for use in conjunction with an elevated shooting platform. A sketch of the proposed configuration is shown in Figure 4.

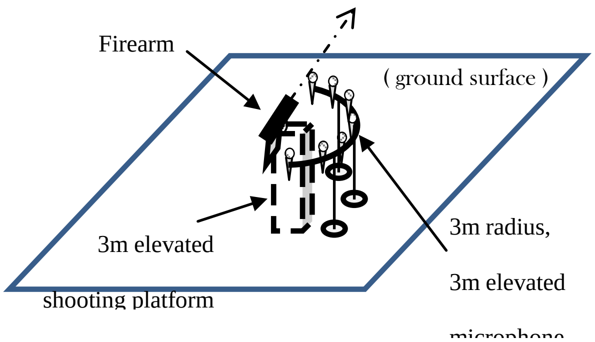

Figure 4: Quasi-anechoic recording using elevated shooting and microphone positions sufficient to delay reflected sound arrival until after the direct sound of the gunshot has been completed.

Note that if there is a concern that a particular firearm under test exhibits a cylindrically asymmetrical directional characteristic, the proposed rig can be adjusted, or more simply, the firearm can be rotated about its firing axis.

The microphone rig is constructed using extruded aluminum struts (80/20-brand material) arranged as four sides of an octagon. The microphones are positioned on short arms attached to the semi-octagonal rig so that the diaphragms are equidistant from the central shooting position, as depicted in Figure 5. The aluminum strut rail is shown in Figure 6. Twelve microphones are mounted along the 3 meter radius semicircle, at azimuths 0°, 16.4°, 32.7°, 49.1°, 65.5°, 81.8°, 98.2°, 114.5°, 130.9°, 147.3°, 163.6°, and 180°.

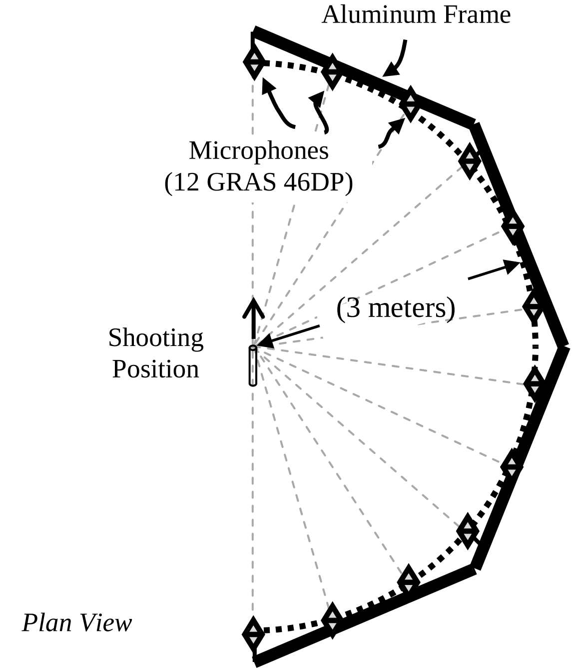

Figure 5: Microphone mounting frame surrounding the shooting position. The frame holds 12 GRAS 46DB 1/8" diaphragm microphones 3 meters from the shooting position and 3 meters above the ground.

Figure 6: Custom-designed aluminum mounting strut frame top rail segments connected to expandable legs for 3 meter elevation.

The microphone selection required consideration of the anticipated sound pressure level and the desired measurement bandwidth. The microphones and preamplifier previously used (DPA 4003 with 130 volt HMA 5000 preamp) have ½" diaphragms, 154dB SPL peak rating, and a usable bandwidth of approximately 20 kHz. A smaller diaphragm microphone provides both greater SPL capability and usable bandwidth. The microphones selected for this project are G.R.A.S. type 46DP microphone sets, consisting of type 40DP 1/8" diaphragm 200 volt externally polarized condenser capsules, type 26TC ¼" preamplifiers, and type 12AA and 12AG power modules providing the 200 volt polarization and 120V preamplifier power (Figure 7). The microphones provide ±2dB frequency response to 140 kHz, with dynamic range specification between 46 dB lower limit and 178 dB upper limit (132 dB dynamic range).

Figure 7: GRAS type 46DP 1/8" microphone and type 12AA power supply.

The audio recording system selected for the project is a National Instruments NI PXIe-1071 chassis equipped with a NI PXIe-8840 Core processor and NI PXIe-6358 data acquisition card. The analog-to-digital system provides sixteen simultaneous inputs, 16-bit resolution, at up to 1.25 MS/s/ch sampling rate. Twelve of the sixteen channels will be used for the semicircular microphone array, and the additional four channels will be used for auxiliary microphones located at the shooting position and also down range.

3.3. Preliminary test progress

Work is currently underway to complete construction of the microphone rig and to conduct the first tests using the multichannel high performance recording system.

The recording system enables a standard methodology for cataloging firearm acoustical characteristics, and creating a database of acoustical gunshot signatures as a function of azimuth for a representative collection of firearms that may be encountered by law enforcement, such as the firearms used in our preliminary experiments:

1. 308 Winchester rifle
2. 223 Remington rifle
3. 12 gauge shotgun
4. 22 long rifle
5. 45 ACP handgun
6. 10 mm auto handgun
7. 40 S+W handgun
8. 357 Magnum handgun
9. 9x19mm handgun
10. 38 Special handgun

4. CONCLUSION

This paper is a progress report on our experimental quasi-anechoic gunshot recording and characterization methodology. The proposed system will provide objective, reliable, and repeatable measurement of gunshot acoustics for a firearm under test. This paper provides current status of the test system, and future publications will include updated information and acoustical data from the gunshot tests.

5. ACKNOWLEDGEMENTS

This work is supported by grant 2014-DN-BX-K034 from the U.S. Department of Justice, National Institute of Justice, Office of Justice Programs (Dr. Gregory Dutton, Program Manager).

6. REFERENCES

[1] Maher, R.C. "Audio forensic examination: authenticity, enhancement, and interpretation," IEEE Signal Processing Magazine, vol. 26, pp. 84-94, 2009.

[2] McGinty, T.J., "Why the Cuyahoga County Prosecutor's Office is spending half a million dollars on dash cams for Cleveland police cars," Cleveland.com, 2015 May. Accessed 1 August 2015. URL: http://tinyurl.com/o737dw8,

[3] Brixen, E.B., "Acoustics of the crime scene as transmitted by mobile phones" Proc. Audio Eng. Soc. 126th Conv., Munich, Germany, preprint 7699, 2009.

[4] Maher, R.C. and S.R. Shaw, "Gunshot recordings from digital voice recorders," Proc. Audio Engineering Society 54th Conference, Audio Forensics—Techniques, Technologies, and Practice, London, UK, 2014 June.

[5] Weissler, P.G., and Kobal, M.T., "Noise of police firearms," J. Acoust. Soc. Am., vol. 56(5), pp. 1515-1522, 1974 November.

[6] Stoughton, R., "Measurements of small-caliber ballistic shock waves in air," J. Acoust. Soc. Am., vol. 102(2), pt. 1, pp. 781-787, 1997 August.

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

[8] 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, 2007 April.

[9] 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, 2010 June.

[10] 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, 1998 July/August.

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

[12] 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, 2011 April.

[13] Maher, R.C., "Acoustical modeling of gunshots using directional information and reflections," Proc. Audio Eng. Soc. 131st Conv., New York, NY, preprint 8494, 2011.

[14] 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, 1998 July/August.