GUNSHOT RECORDINGS FROM DIGITAL VOICE RECORDERS

ROBERT C. MAHER AND STEVEN R. SHAW

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

Audio forensic gunshot recordings may come from telephone conversations and land mobile radio traffic recorded at an emergency call center, electronic news gathering activities, surveillance recordings, etc. As an increasing number of law enforcement officers carry digital voice recorders to help document their interactions with citizens and suspects, it has become common for audio forensic examiners to encounter gunshot evidence from voice recorders. Because these off-the-shelf devices incorporate microphones, electronics, and digital coding algorithms intended to capture intelligible human speech and not gunfire, the examiner must consider the strengths and weaknesses of the portable digital voice recorder when interpreting forensic audio gunshot evidence.

INTRODUCTION

Audio forensic gunshot evidence may be encountered in law enforcement investigations, particularly when there is a need to reconstruct the geometry and time sequence of events at a crime scene from available acoustic recordings [1-3]. The recordings may come from a dispatcher or emergency call center recording system, a surveillance or electronic newsgathering system, or, as is increasingly common, a *digital voice recorder* carried by law enforcement officers at the scene of a shooting incident [4-5].

Since the widespread availability of tape recorders in the 1950s, law enforcement officers have used audio and video recording systems to document investigative interviews and interrogation sessions. For the past 20 years the use of in-car Mobile Video Recorder (MVR) dashboard-mounted video camera systems has become more widespread for police cruisers, and 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 his or her actions as a way to protect against unfounded allegations of misconduct.

Because the use of these recording systems is becoming ubiquitous, it is increasingly common for audio forensic examiners to evaluate data collected by these systems, including audio forensic gunshot evidence. Thus, it is important for forensic examiners to understand the strengths and weaknesses of the audio recording systems used in mobile audio recorders, particularly the miniature digital voice recorders carried by many law enforcement officers.

This paper is organized as follows. First, we review the principal acoustical characteristics of gunshot sounds, focusing upon a 9 mm handgun similar to the firearms carried by many law enforcement officers in the United States. Next, we describe the experiments we conducted to record the sound of the 9 mm handgun using a consumer-grade digital voice recorder and a professional audio recording system under field conditions, including having the recorders located inside a parked vehicle. We show several representative recordings to illustrate the issues. Finally, we conclude with several observations and recommendations for audio forensic gunshot examiners.

1 REVIEW OF GUNSHOT ACOUSTICS

A conventional firearm uses the hot, expanding gas produced by the rapid combustion of gun powder to propel the projectile out of the gun barrel. The expanding combustion gases escape the muzzle end of the barrel, causing an abrupt acoustic pressure disturbance and muzzle blast shock wave [6-8].

The gunshot acoustic disturbance is directional, and the waveform details vary with azimuth relative to the on-axis orientation of the barrel [9-11]. If the projectile is traveling at a speed greater than the local speed of sound in air, the acoustic disturbance downrange near the bullet's path will include an acoustic shockwave cone trailing the bullet's supersonic trajectory [8].

For typical handguns the duration of the acoustical muzzle blast disturbance is only a few milliseconds. An example of a handgun recording obtained anechoically (truncated before the arrival of the first reflection) with the microphone nearly on-axis is shown in Figure 1 [10].

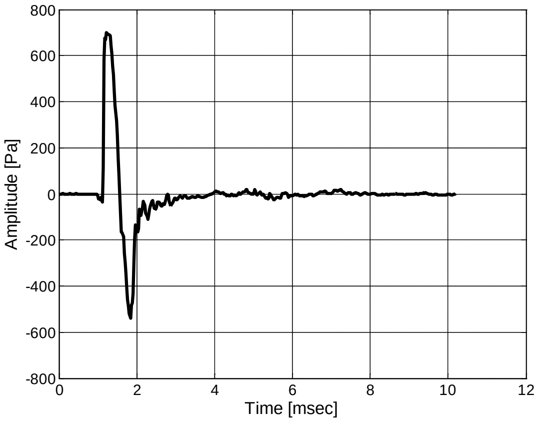

Figure 1: Anechoic recording of single gunshot, Glock 19 handgun, 9 mm ammunition. 24-bit, 48 kHz PCM, professional microphone at 3 meters, 9° off-axis. Peak level 151 dB SPL re 20 μPa.

While the direct-sound muzzle blast duration is quite brief, an ordinary audio recording of a gunshot will generally include a much longer acoustic response representing the discrete sound reflections from the ground and nearby objects and the reverberation tail of the acoustical surroundings [12]. The short duration of the gunshot is essentially an impulsive acoustical doublet, so any analysis of more than the first few milliseconds of the gunshot will generally contain more information about the acoustical surroundings than it does about the firearm itself.

A reverberant recording of the same firearm from Figure 1 is shown in Figure 2, with a correspondingly longer time axis. The recording in Figure 2 was obtained at a shooting range with various buildings, sheds, berms, parked vehicles, etc., in the surrounding area. The microphone was placed behind a parked vehicle approximately 8 meters from the firearm, simulating an inadvertent recording situation.

2 DIGITAL VOICE RECORDERS

The gunshot recordings depicted in Figures 1 and 2 are not typical audio forensic gunshot evidence because these recordings do not exhibit clipping or other indications of waveform distortion generally found in recordings that are not made under carefully controlled circumstances. By comparison, if a gunshot is recorded by a consumer-level digital voice recorder using its built-in microphone, the situation is likely to overload the microphone and the input stage of the recorder, and this clipped and distorted waveform is then presented either to a lossy digital audio perceptual compression algorithm such as MP3, or a lossy digital speech coding algorithm such as VSELP. In either case the details of the gunshot acoustic waveform are not guaranteed to be preserved.

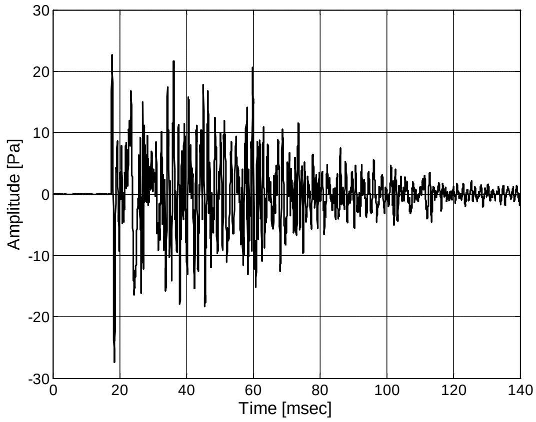

Figure 2: Reverberant recording of single gunshot, Glock 19 handgun, 9 mm ammunition. 24-bit, 48 kHz PCM, professional microphone at 8 meters, 90° off-axis. Peak level 123 dB SPL re 20μPa.

2.1 Digital voice recorders and gunshot sounds

An example gunshot recording was made using a digital voice recorder. The recorder was an Olympus brand, model VN-702PC, purchased at a retail office supply store. The pocket-sized recorder (Figure 3) is marketed for recording speeches, lectures, and other voice conversations. The device is equipped with a USB port, so recorded files can be uploaded and downloaded to a personal computer or another device with USB capability.

Figure 3: Example consumer digital voice recorder used in the tests: Olympus brand, model VN-702PC.

The recorder was set for MP3 format with 192 kbps rate, and the built-in microphone was used. The recorder was placed 3 meters from the handgun at approximately 9° off-axis from the muzzle. The resulting decoded (uncalibrated) recording uploaded from the device is shown in Figure 4.

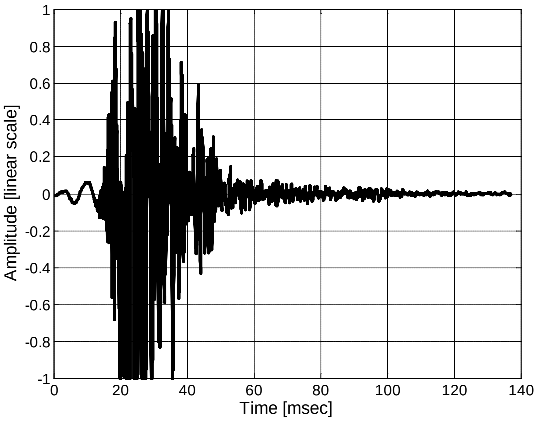

Figure 4: Reverberant recording of single gunshot, Glock 19 handgun, 9 mm ammunition. MP3, consumer digital voice recorder with built-in microphone at 3 meters from shooting position, 9° off-axis.

The digital voice recorder waveform presents several interpretation issues. The initial response to the gunshot is smeared in time, partially due to the MP3 encoder block length (roughly 25 ms), and also the microphone and preamp behavior for the abrupt, high-amplitude acoustical signal. Identifying the initial onset of the gunshot is difficult compared to the controlled recordings, as it appears spread over a 5-10 ms span. 10 ms represents more than 3 meters at the speed of sound, so this time uncertainty may be an issue for forensic investigations because the relative position of multiple possible shooters and microphone may be an issue in dispute.

2.2 Effect of automatic gain control

Digital voice recorders often include automatic gain control (AGC) features that the manufacturer includes as a helpful means for the user to get intelligible voice recordings under a variety of possible recording scenarios. To investigate whether the AGC might contribute to waveform distortion for abrupt sounds like gunshots, we performed a laboratory experiment to measure the behavior of the voice recorder for a high-level 500 Hz sinewave burst (rectangular envelope). The resulting signal recording is shown in Figure 5.

The recorded waveform initially clips, and then this particular voice recorder appears to do a step-wise gain reduction of 1 dB every 25 ms over the period of about 0.5 seconds before reaching steady-state. Upon release of the input tone burst, the automatic gain control takes about 1 second to release its gain reduction. Thus, for this particular recorder it appears that the rate of AGC action is too slow to have much effect upon a single non-reverberant gunshot event lasting under 20 ms, but the AGC could alter the amplitude characteristic for a gunshot in the presence of reverberation, or if there was a barrage of shots spanning a few seconds or more. In these cases the AGC action would need to be included in the waveform interpretation.

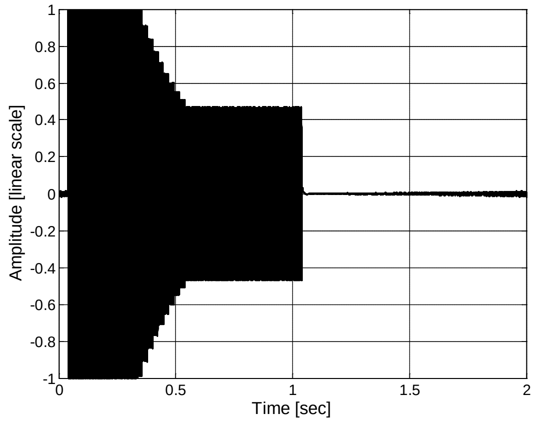

Figure 5: Response of digital voice recorder to 500Hz tone burst. Initial clipping with automatic gain reduction attack requiring 0.5 seconds, and approximately 1 second gain reduction release.

2.3 Voice recorders and audio forensic analysis

The particular behavior of the digital voice recorder used in this study demonstrates some of the issues likely to be encountered in other digital voice recorder systems, but its features may or may not be representative of all similar products. Audio forensic examiners may encounter many different digital voice recorders and proprietary recording methods used by emergency dispatch centers, remote recording devices, and audio/video surveillance systems, and therefore must be careful to understand the capabilities, strengths, and weaknesses of the system, particularly for non-speech signals such as gunshots.

3 ADDITIONAL GUNSHOT EXPERIMENTS: RECORDING WITHIN A VEHICLE

Audio forensic gunshot recordings are sometimes obtained from pocket-sized digital voice recorders carried by officers within a police cruiser or some other law enforcement vehicle. In addition to the portable digital recorders, some police vehicles have built-in video cameras and fixed microphones located in the cabin, and some systems also include wireless microphones worn by the law enforcement officers that tie into the audio/video recording system.

If the law enforcement officer is within a police cruiser and witnesses a firearm discharge outside the cruiser, the acoustic signal may be recorded by the digital voice recorder in the officer's pocket and/or by the wireless microphone tied into the cruiser's audio/video recording system, if so equipped.

To investigate this recording scenario, we conducted a sequence of gunshot experiments using a handgun fired outside a mid-sized sport utility vehicle, parked with the engine off, while a professional audio recorder and a consumer digital voice recorder were recording the sound inside the vehicle. Recordings were made with the vehicle doors and windows closed, and also with doors closed but the driver's window open. The handgun was located 7 meters perpendicular to the driver's window pointed in a direction parallel to the vehicle, meaning that the gun barrel was oriented 90° off-axis with respect to the driver's window of the vehicle. The test configuration is depicted in Figure 6.

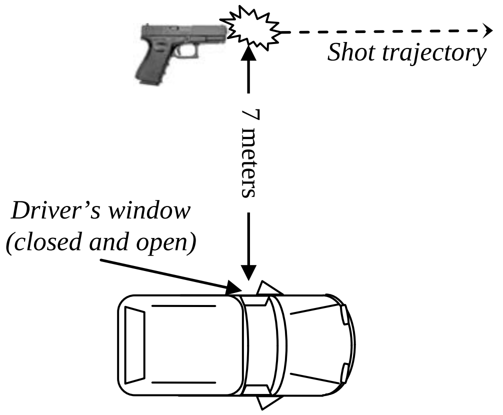

Figure 6: Experimental configuration for external gunshot recorded inside a parked vehicle.

As it was infeasible to synchronize the PCM and MP3 recorders, the gunshot recordings depicted in Figures 7-12 are not time-aligned with each other. Instead, the waveform segments shown here have a manually specified time zero reference that is approximately 15-20 ms prior to the muzzle blast arrival.

3.1 Exterior gunshot recorded inside closed vehicle

With the vehicle's doors and windows closed, the acoustic recording using the professional microphone shows many of the reverberant characteristics of the open-air recording, although the sound amplitude is significantly reduced by being inside the closed vehicle. The recording is shown in Figure 7.

The same gunshot was recorded simultaneously in the closed vehicle using the Olympus brand VN-702PC digital voice recorder. The digital voice recorder waveform is shown in Figure 8. Note that the recordings of Figure 7 and Figure 8 were obtained using different recording devices, so the time axes are manually aligned for the figures. The voice recorder's automatic gain control was likely in its high-gain state due to the relatively quiet interior of the vehicle prior to the gunshot, so even with the gunshot sound attenuated by the closed window the level was still sufficient to clip the recorder's input stage. As was previously noted for the open-air recordings, the voice recorder again exhibits a significant amount of time smearing at the onset of the gunshot sound, partially due to the MP3 block size and the behavior of the voice recorder's microphone and input stage.

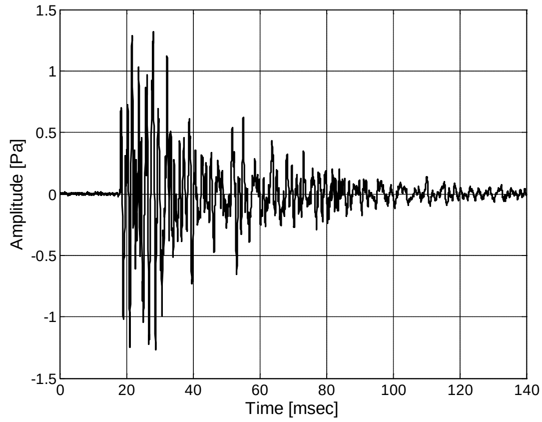

Figure 7: Recording of single gunshot, Glock 19 handgun, 9 mm ammunition. 24-bit, 48 kHz PCM, professional microphone inside closed vehicle, 7 meters from shooting position, 90° off-axis.
Peak level 96 dB SPL re 20μPa

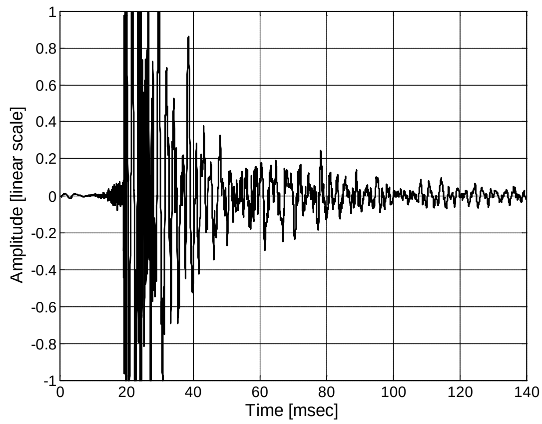

Figure 8: Recording of single gunshot, Glock 19 handgun, 9 mm ammunition. MP3, consumer digital voice recorder with built-in microphone inside closed vehicle, 7 meters from shooting position, 90° off-axis.

3.2 Exterior gunshot recorded inside open vehicle

Additional recordings were made for the situation in which the driver's side window was open rather than closed. The handgun was again fired from the location 7 meters perpendicular to the driver's window and oriented 90° off-axis. The resulting open-window audio recordings are shown in Figures 9 and 10 for the professional audio recorder and for the digital voice recorder, respectively. These recordings show the presence of background noise and slight wind turbulence at the open window, which accounts for the non-zero signal level prior to the arrival of the gunshot transient. The signal behavior in the time interval surrounding the gunshot transient is shown with a zoomed time scale in Figures 11 and 12.

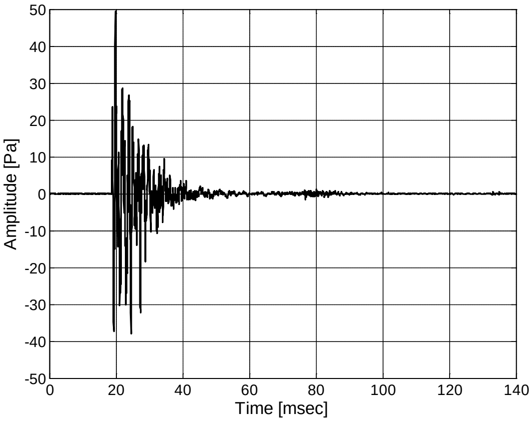

Figure 9: Recording of single gunshot, Glock 19 handgun, 9 mm ammunition. 24-bit, 48 kHz PCM, professional microphone inside open window vehicle, 7 meters from shooting position, 90° off-axis. Peak level 128 dB SPL re 20μPa.

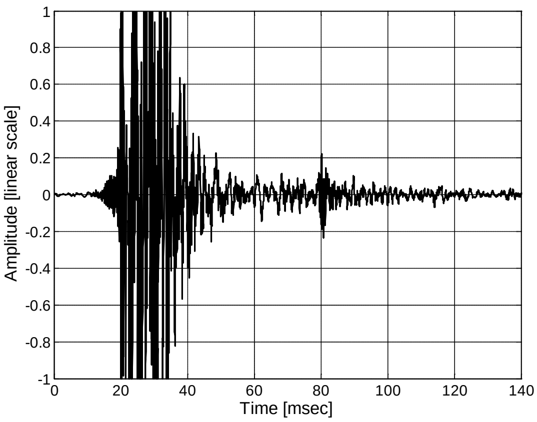

Figure 10: Recording of single gunshot, Glock 19 handgun, 9 mm ammunition. MP3, consumer digital voice recorder with built-in microphone inside open vehicle, 7 meters from shooting position, 90° off-axis.

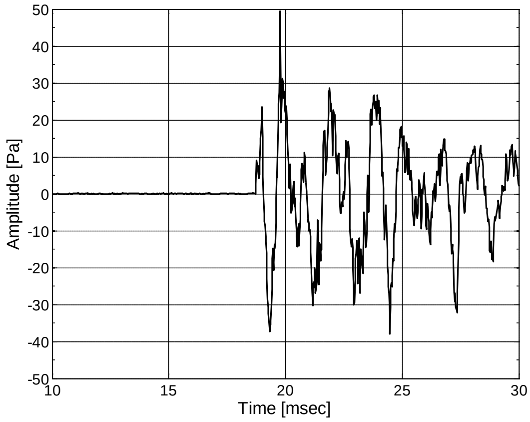

Figure 11: Gunshot recording, professional recorder (PCM) from Figure 9, time range 10-30 ms.

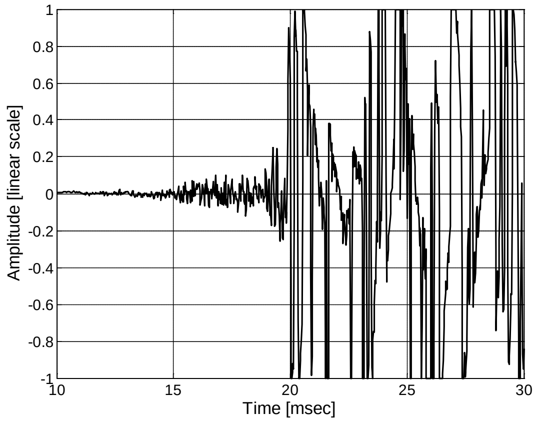

Figure 12: Gunshot recording, digital voice recorder (MP3) from Figure 10, time range 10-30 ms.

The primary difference between the open-window and close-window recordings is the sound level: the interior sound is substantially higher with the window open, as would be expected. A secondary effect is that the spectral content of the reverberant gunshot is greater with the window open: the closed window exhibits greater attenuation of the high frequency content of the gunshot than the open window case, presumably due to the vehicle's glass being more highly reflective for shorter sound wavelengths.

3.3 Vehicle gunshot summary

With the prevalence of digital audio recording systems in use by law enforcement officers, gunshots in the vicinity of a law enforcement vehicle are increasingly likely to be captured by an audio recording system permanently installed in the cruiser, or by a digital voice recorder carried on the officer's belt or in a uniform pocket. Even with the doors and windows closed, a gunshot outside the vehicle may lead to a sound level inside the vehicle sufficient to overload and clip the digital voice recorder's input section. The combination of signal clipping, reverberation due to acoustical reflections, and effects of the perceptual coding algorithm (e.g., MP3) that may be a feature of the recording system, may cause the audio forensic evidence to be a complicated and difficult to interpret waveform. Some conclusions may still be drawn from such inherently distorted audio forensic evidence, but care must be taken to avoid misinterpreting the timing, sound level, and spectral characteristics of such signals.

4 CONCLUSIONS

Audio forensic gunshot evidence can be encountered in a variety of investigations. Gunshots relevant to an investigation may come from a dispatcher or emergency call center recording system, a surveillance or electronic newsgathering system, or from a digital voice recorder carried by someone at the scene of a shooting incident.

Common investigative questions from an incident involving firearms include determining the location and orientation of the shots, distinguishing between sounds from different guns, and reconstructing the sequence of events, e.g., who shot first, what utterances and background sounds are present, and correlating the acoustic evidence with physical evidence from the scene, such as recovered bullets and spent shell casings.

In some cases it may be possible that multiple simultaneous audio recordings are available due to the presence of more than one recording device at the scene. If the recording devices were located at known positions, it may be feasible to synchronize the timelines by identifying common sound events in the multiple recordings, taking into account the time-of-arrival differences attributable to the geometric spacing between the shooting positions and the recording positions.

However, based on the experiments reported in this paper and on other examples taken from actual law enforcement investigations, audio forensic examiners need to use care before assuming that a device intended to record intelligible speech will be able to capture precise time and amplitude information for gunshots.

The two fundamental issues for digital voice recorders are amplitude overload (clipping) due to the signal exceeding the input range of the device, and the effects of the digital coding algorithm on the waveform both in terms of time smearing and waveform detail. These issues will contribute to uncertainty about findings related to the waveform details. The audio forensic examiner must be very cautious to understand the shortcomings of the recording system, and explain these matters to the client or the court.

Nevertheless, there will be many instances in which the audio forensic examiner is asked either to corroborate or to refute physical evidence, testimony, or ear-witness accounts based on evaluation of the order in which different audible events occurred at the shooting scene and the relative timing of those audible events. In these cases the availability of digital voice recorder evidence can be practical and useful as long as the inherent limitations of the recording devices are properly taken into account.

REFERENCES

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

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

[3] J.C. Freytag and B.M. Brustad, "A survey of audio forensic gunshot investigations," *Proc. AES 26th International Conf., Audio Forensics in the Digital Age*, Denver, CO, paper 6-1 (2005).

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

[5] J. Stanley, "Police body-mounted cameras: with right policies in place, a win for all," *American Civil Liberties Union*, position paper, https://www.aclu.org/files/assets/police_body-mounted_cameras.pdf, (2013).

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

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

[8] R.C. Maher and S.R. Shaw, "Deciphering gunshot recordings," *Proc. Audio Engineering Society 33rd Conf., Audio Forensics—Theory and Practice*, Denver, CO, paper 2 (2008).

[9] P. Rasmussen, G. Flamme, M. Steward, D. Meinke, and J. Lankford, "Measuring recreational firearm noise," *Sound and Vibration*, August 2009, pp. 14-18 (2009).

[10] R.C. Maher and S.R. Shaw, "Directional aspects of forensic gunshot recordings," *Proc. Audio Eng. Soc. 39th Conf., Audio Forensics--Practices and Challenges*, Hillerød, Denmark, paper 4-2 (2010).

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

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