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Measured directionality of firearm muzzle blast sounds for audio forensic analysis

Robert C. Maher

Electrical and Computer Engineering, Montana State University, Bozeman, MT 59717-3780

Correspondence should be addressed to `rmaher@montana.edu`

ABSTRACT

When triggered, conventional firearms produce a loud impulsive report known as the muzzle blast. In this paper we present the measured directional sound characteristics of muzzle blast sounds from several common firearms and discuss the implications for audio forensic analysis. While the muzzle blast sound is frequently assumed to be omnidirectional, quasi-anechoic measurements show that the sound pressure level can vary by more than 20 dB between the sound level in the direction the barrel is pointing and the sound level off to the side or behind the gun. The directionality of the muzzle blast may provide a useful clue in some audio forensic cases, while also introducing a complicating factor for gunshot detection and classification when the orientation of the firearm with respect to the microphone is often unknown. As described in this paper, research involving machine learning for firearms detection and classification requires data sets for training that truly represent the directional variability of real gunshot sounds.

1 Introduction

Firearms crimes are common in law enforcement investigations in the United States. One specialty of audio forensic analysis considers how recordings of gunshot sounds can help inform the court regarding the circumstances of a firearm incident. Audio forensic interpretation may include determining the number and order of shots in a sequence, the likely type of guns involved, and the position and orientation of the firearms [1][2].

A growing number of law enforcement organizations require officers to use body-worn and in-vehicle recording devices, and many private citizens now utilize home surveillance systems that record audio. It is also increasingly common for bystanders at incidents involving firearms to create audiovisual recordings using their mobile phones, and these recordings may capture the sound of gunfire.

A common misconception among audio forensic examiners and gunshot detection system providers is that gunshot muzzle blast sounds emanate like an omnidirectional acoustic impulse traveling equally in all directions from the gun. Our research shows that the muzzle blast sounds from conventional firearms are very directional, with sound energy concentrated primarily in the direction the barrel is pointing. While the typical muzzle blast from firearms forms a cylindrically symmetrical sound field about the axis of the barrel, the sound level and acoustic wave details vary significantly in the azimuthal direction [3][4][5].

As described below, this research is based upon experimentally observed directionality of several common handguns and rifles measured using a special quasi-anechoic audio recording technique [6][7].

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.

Thus, the empirical observations summarized in this paper are important to share with the gunshot automatic detection and recognition community, especially because of attempts to utilize machine learning methods: the training data must include realistic variations that account for the directionality of the firearm sounds, not random and highly-reverberant sound effects recordings that do not encompass the true parameters of actual firearm muzzle blast sounds.

The remainder of this paper is organized as follows. First, we summarize the common acoustical attributes of muzzle blast sounds from conventional firearms. Next, we describe the methodology and rationale for the quasi-anechoic directional sound measurement technique used to collect these data. Finally, we present example directional patterns measured for ten different firearms, and provide some concluding remarks.

2 Firearm sounds

In the United States, firearms of interest in audio forensic analysis span the range of long guns (rifles and shotguns), and handguns of various types (pistols and revolvers). Contemporary firearms generally have a magazine or cylinder carrying multiple rounds of ammunition, allowing successive shots to be fired rapidly [1].

A conventional firearm uses ammunition consisting of a cartridge containing a bullet crimped onto a hollow metal casing filled with gunpowder propellent. Rapid combustion of the gunpower within the casing creates a hot, expanding gas mixture that propels the bullet from the casing, through the gun barrel, and out of the muzzle. The abrupt pressure disturbance of the expanding gas emitted from the barrel as the bullet leaves the gun is referred to as the *muzzle blast*, which typically has a duration of just a few milliseconds [8][9].

The direct sound of the muzzle blast is the primary acoustical signal from the firearm. The details of the muzzle blast sound are attributable to many factors, including the amount and composition of the ammunition's propellent load, the weight and shape of the bullet, slug, or buckshot comprising the ammunition, the length, diameter, and details of the gun barrel, and other physical factors.

Audio recordings of gunshots have characteristics that depend upon the location of the microphone with respect to the gun barrel, and the presence of acoustic reflections, reverberation, and background noise. Audio forensic examiners will encounter gunshot sounds recorded by body-worn cameras just centimeters from the firearm, recordings from bystander videos or surveillance cameras a few tens of meters from the gun, and also audio from recording systems such as ShotSpotter, that may be 500 or more meters from the firearm. Therefore, the recording of a gunfire incident will generally contain a mixture of direct, diffracted, and reflected sounds, and may exhibit distortion due to limitations of the microphone and preamplifier electronics, as well as the common use of perceptual audio compression (e.g., MP4).

The directional characteristics of the muzzle blast sound from a firearm can be important in several fields, including hearing conservation, community noise studies, gunshot detection, and audio forensic examination of crime scene recordings. Investigators often characterize gunshot sounds using a single measurement obtained by a sound level meter, with the microphone positioned 90° from the barrel's trajectory, 1.6 meters above the ground, and 1 meter off to the side. Specialized measurements for noise associated with human hearing protection include U.S. Department of Defense standard 1474E [10], but because the standard is intended to guide studies of sound pressure at the ears of a human subject when a firearm is used in its conventional manner, the presence of reflected sound from the ground is included in the measurement.

However, for audio forensic analysis purposes it is desirable to characterize the direct sound emanating from the firearm without the interference of acoustic reflections, so a non-standard set of measurement procedures were used for the current study, as described in the next section.

3 Quasi-anechoic directional measurement methodology

The primary scientific tasks of the research reported in this paper are measuring the directional sound pressure level and documenting the directional waveform characteristics of a firearm's muzzle blast. The technical challenges of this study include accommodating the high acoustical sound pressure associated with gunshots, and the need to avoid the presence of sound reflections that would interfere with measuring the sound produced by the firearm.

Accommodating high sound pressures requires careful selection and placement of the measurement microphones, and avoiding sound reflections requires careful consideration of reflecting surfaces near the firearm and the microphones.

There was no suitable anechoic chamber available that would allow the discharge of firearms. Instead, we created a quasi-anechoic measurement procedure for use at an outdoor shooting range. The concept was to use an open field with no nearby obstacles, then to raise the firearm and the measurement microphones above the ground sufficiently that the muzzle blast can be recorded in its entirety before the first acoustical reflection from the ground arrives at the microphone. The recording can be truncated to remove the reflection.

Prior reports and experiments showed that the muzzle blast duration for the firearms of interest was less than 10 milliseconds. Therefore, to have the ground reflection arrival delayed by at least 10 milliseconds, we needed the reflection path muzzle-ground-microphone to be at least 3.4 meters longer than the direct path muzzle-microphone, assuming the speed of sound was 343 m/s (at 20° C). Choosing the height to be 3 meters and the radial distance from the muzzle to the microphones to be 3 meters, the path length difference between the direct sound and the reflected sound would be 3.7 meters, as sketched in Figure 1 [6].

Prior reports and experiments indicated that the peak sound pressures in the vicinity of the muzzle could be 6000 pascal or more (~170 dB SPL re 20 µPa), depending upon the firearm and ammunition load. The microphones chosen were 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. The microphones provide a ±1 dB frequency range from 10 Hz to 25 kHz (±2 dB from 6.5 Hz to 140 kHz), and dynamic range upper limit of 178 dB SPL. These microphones have relatively low sensitivity, nominally 1mV/Pa, allowing convenient analog audio signal amplitudes with the amplifiers and A/D converters [7].

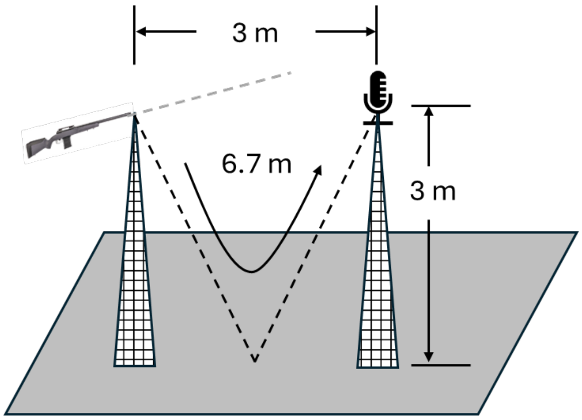

Figure 1: Depiction of the elevated gun and microphone geometry used to ensure that the first acoustic reflection (ground) arrives at the microphone after the entire duration of the muzzle blast has been recorded.

The directional measurement apparatus consisted of a semicircular set of twelve microphones uniformly spaced between 0° and 180°, and mounted on an aluminum bracket with extensions to place each microphone 3 meters from the center of the circle where the firearm's muzzle was positioned. The mounting bracket and the firearm were elevated 3 meters above the ground at an open shooting range.

Figure 2: Recording apparatus with semicircular arc of twelve microphones elevated 3 meters, and marksman positioning firearm muzzle at center of arc.

Figure 3: Each firearm had ten successive shots recorded.

The audio recording system used was 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 provided sixteen simultaneous inputs with 16-bit resolution. Each channel was sampled at a 500kHz sampling rate. The microphones were calibrated using a G.R.A.S. type 42AB calibrator at 250 Hz (114 dB SPL with reference to 20µPa).

4 Measured directional patterns for several firearms

Among the challenges of interpreting the amplitude of gunshot sounds is the choice between peak sound pressure or an average sound pressure calculation of some kind. Our recordings with a 500kHz sampling rate showed the presence of a strong pressure spike of short duration at the onset of the muzzle blast, followed by the brief amplitude fluctuations lasting a few milliseconds. With lower audio sampling rates and recording bandwidths, the amplitude of the initial pressure spike is substantially reduced or even absent in the recording, making any measurement of peak sound pressure ambiguous. Instead, the RMS effective pressure (root-mean-square) for a 10ms time window time aligned with the muzzle blast is used. The sound pressure level (SPL) is calculated using the RMS sound pressure with respect to 20µPa. An example waveform and its effective pressure for a 10ms window is shown in Figure 4.

Tests were conducted with ten firearms (see Table 1), with up to ten successive shots recorded for each gun. While the selection of firearms is not exhaustive, the goal was to use a representative group of firearms to demonstrate the similarities and differences among the directional responses.

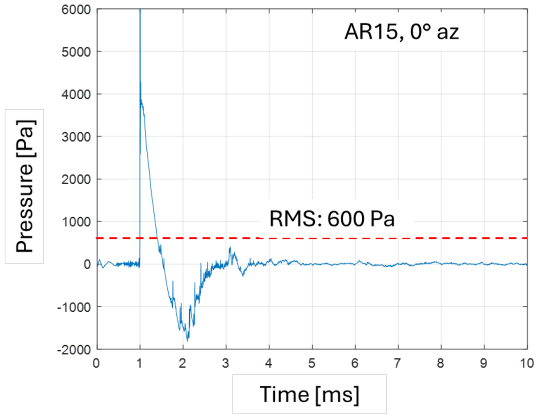

Figure 4: Muzzle blast example at 3 meters from AR15 rifle, 0° azimuth; calculated 600 Pa RMS pressure over a 10ms window. The corresponding SPL is 149.5 dB re 20µPa.

Type	*Model*	*Ammunition Description*	*Fig.*
Rifle	Custom	.308 Winchester, 175 gr	5
Rifle	Stag AR15	Lake City 5.56x45mm, 62 gr	6
Rifle	CZ-452	Fiocchi 22 FLRN, 40 gr	7
Shotgun	Remington 870	12 ga, 3” 00 Buck	8
Handgun	Glock 19	9mm Luger, 135 gr	9
Handgun	Glock 23	.40 S&W, 180 gr	10
Handgun	Sig 239	.357 SIG, 125 gr	11
Handgun	Ruger SP101	.38 Special +P, 158 gr	12
Handgun	Ruger SP101	.357 SIG, 125 gr	13
Handgun	Colt M1911A1	.45 ACP, 230 gr	14

Table 1: List of ten firearms used in the directional testing.

In many cases of interest to audio forensic examiners, the orientation of the firearm with respect to the recording microphone is not known. Thus, the directional information observed in this experiment should give a sense of caution about interpreting differences in gunshot sound levels when successive shots are observed: a difference in level could indicate shots from different firearms, but the difference could also be attributable to a single firearm shooting successive shots in different directions.

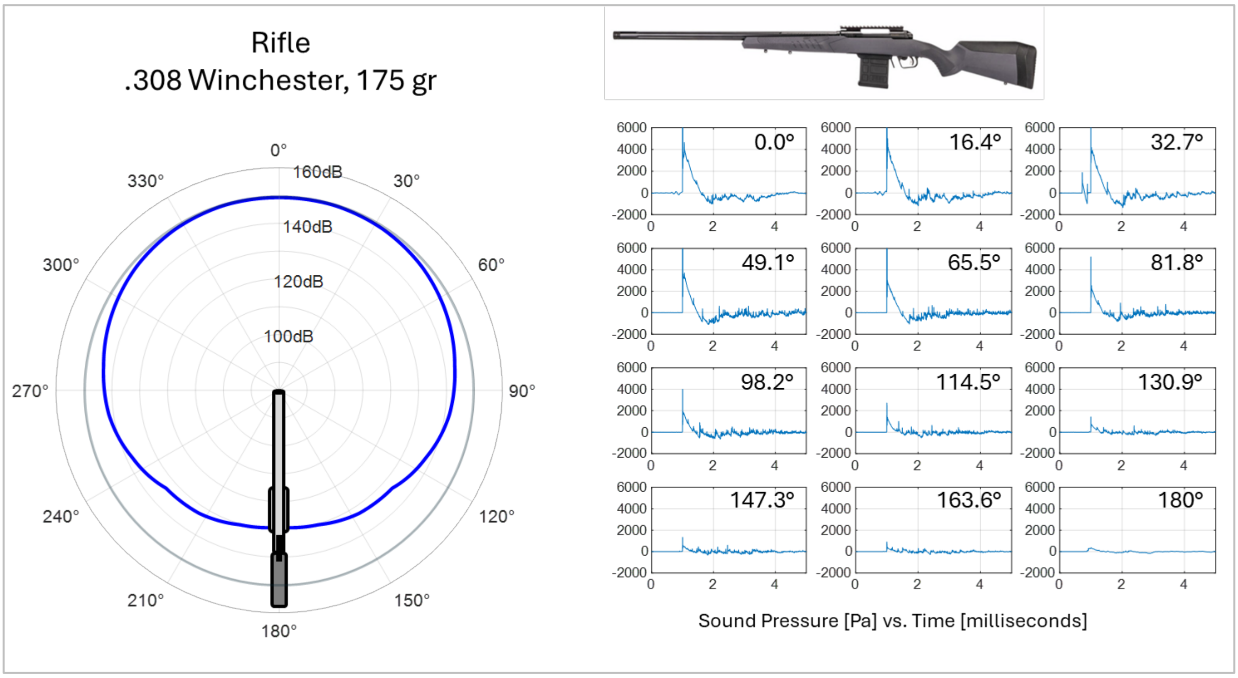

Figure 5: Sound level directional pattern and recordings for .308 rifle (front to back difference 20dB). A ballistic shock wave of the supersonic bullet precedes the muzzle blast (only visible for 32.7° azimuth due to time window).

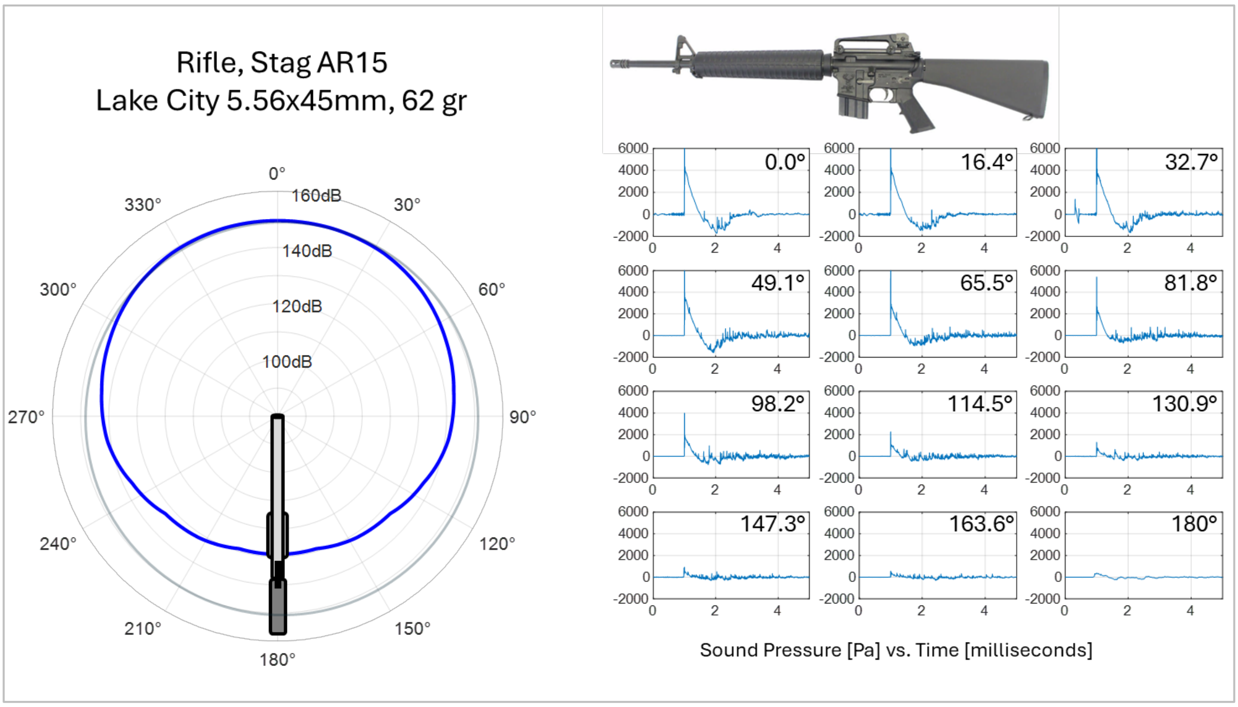

Figure 6: Sound level directional pattern and recordings for AR15 rifle (front to back difference 20 dB). A ballistic shock wave of the supersonic bullet precedes the muzzle blast (only visible for 32.7° azimuth due to time window).

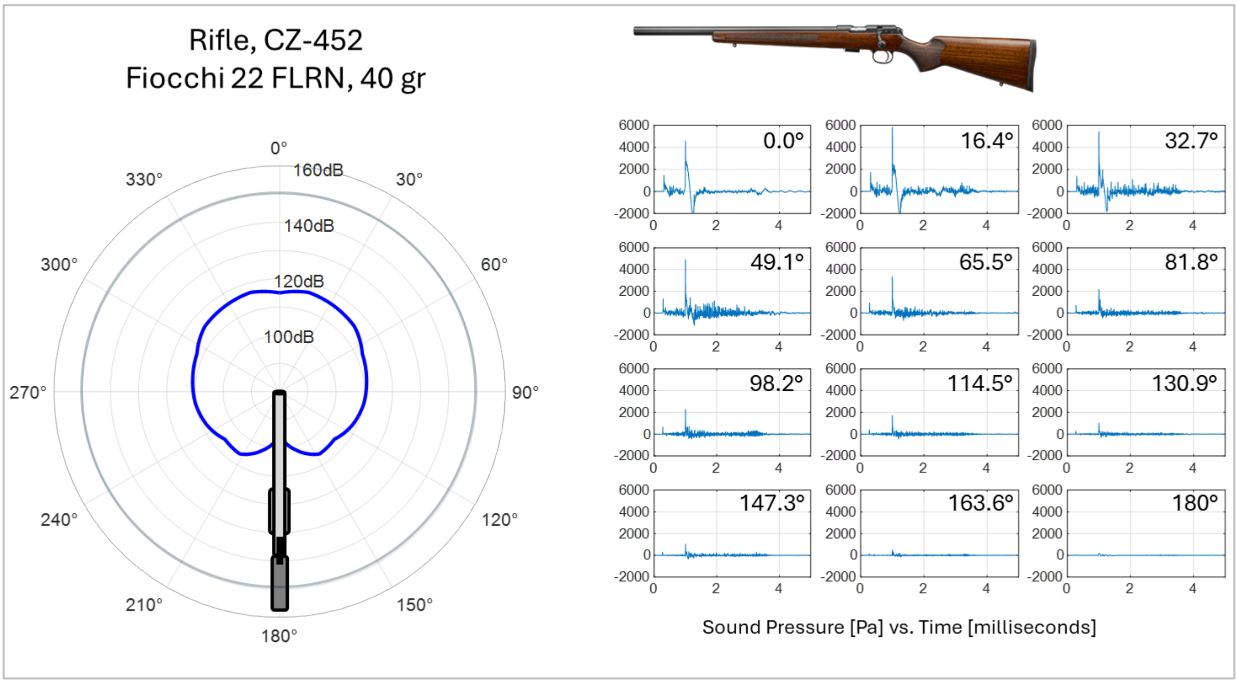

Figure 7: Sound level directional pattern and recordings for CZ-452 22 rifle (front to back difference 10 dB)

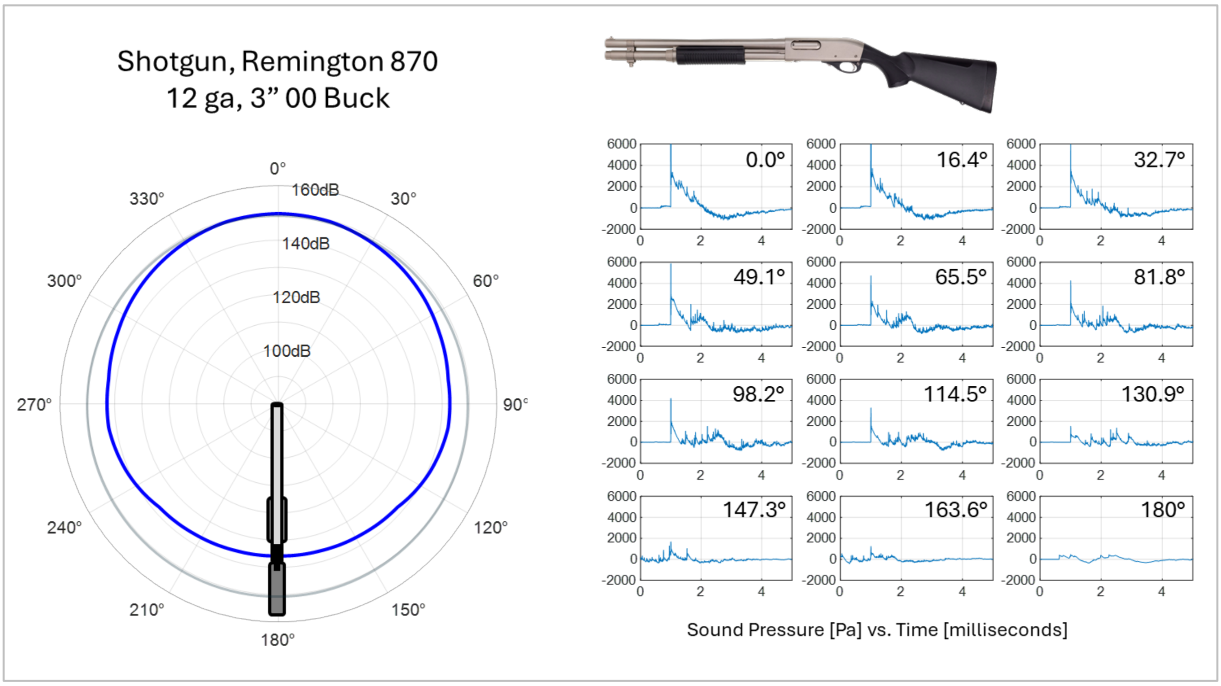

Figure 8: Sound level directional pattern and recordings for Remington 870 shotgun (front to back diff 7 dB).

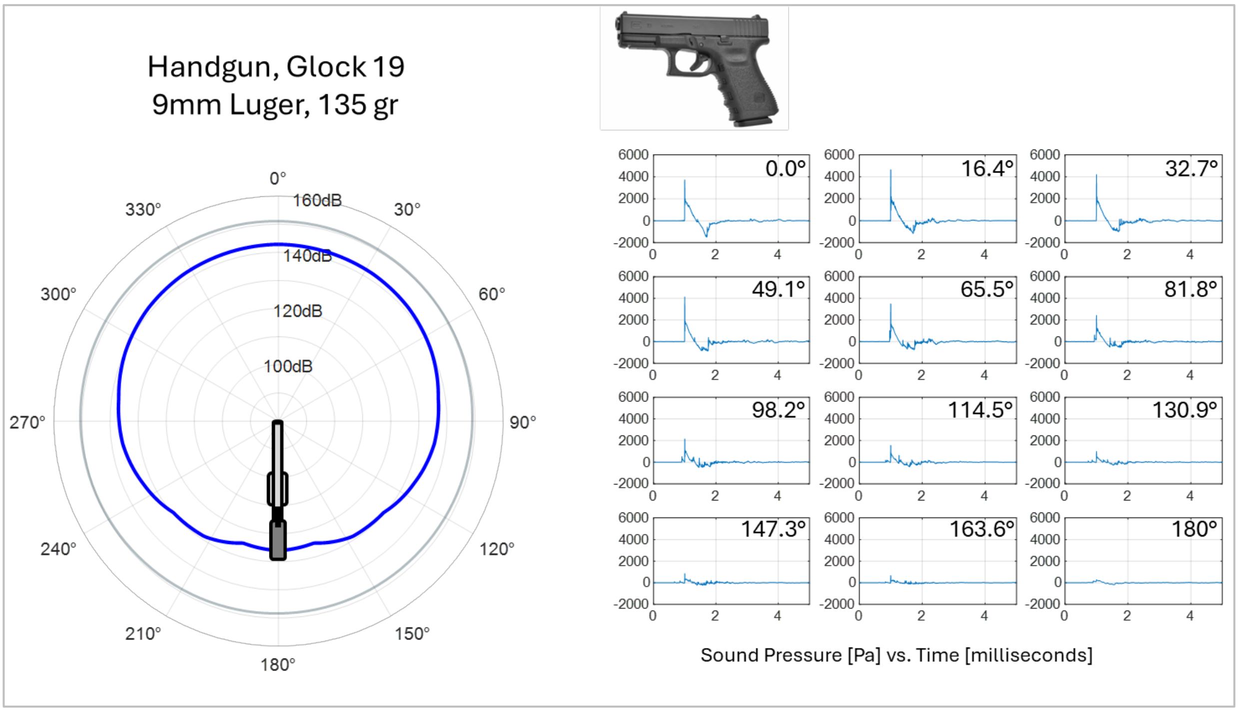

Figure 9: Sound level directional pattern and recordings for Glock 19 handgun (front to back diff 15 dB).

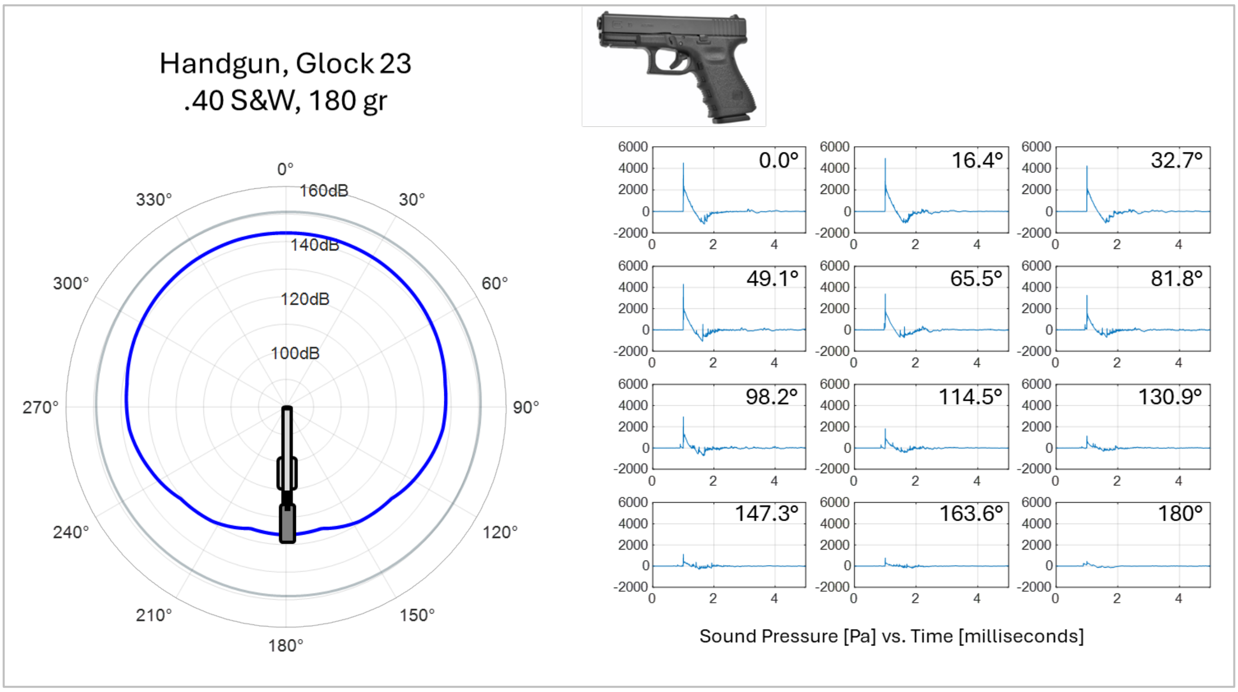

Figure 10: Sound level directional pattern and recordings for Glock 23 handgun (front to back diff 15 dB).

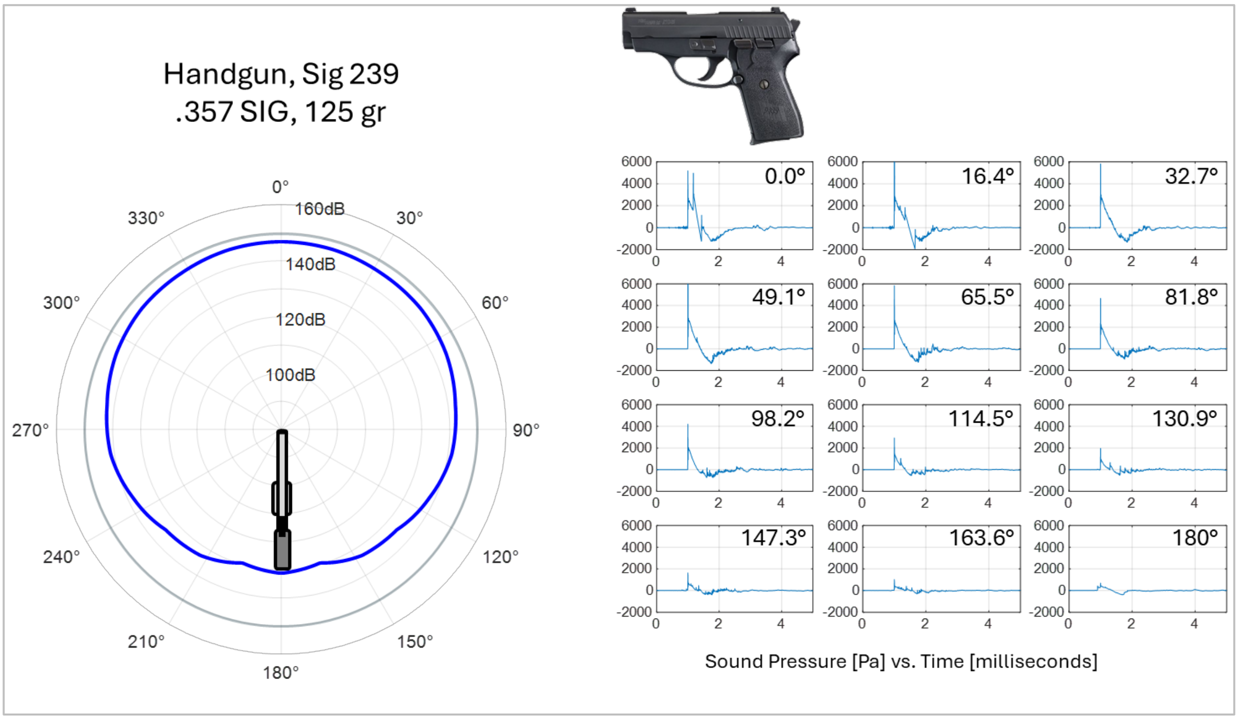

Figure 11: Sound level directional pattern and recordings for Sig 239 handgun (front to back diff 15 dB).

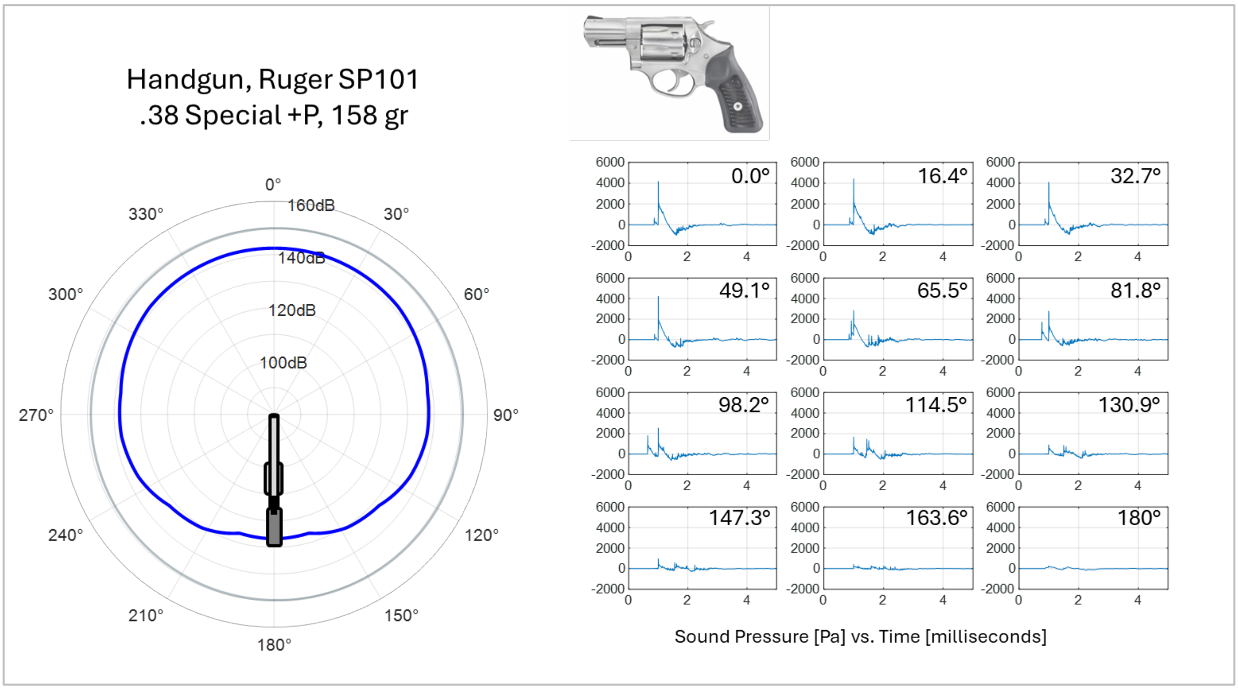

Figure 12: Sound level directional pattern and recordings for Ruger SP101 .38 handgun (front/back diff 10 dB). Note that sound impulse emanating from the cylinder gap of the revolver is observed for the recordings with azimuths wider than 81.8°, giving a double impulse [11].

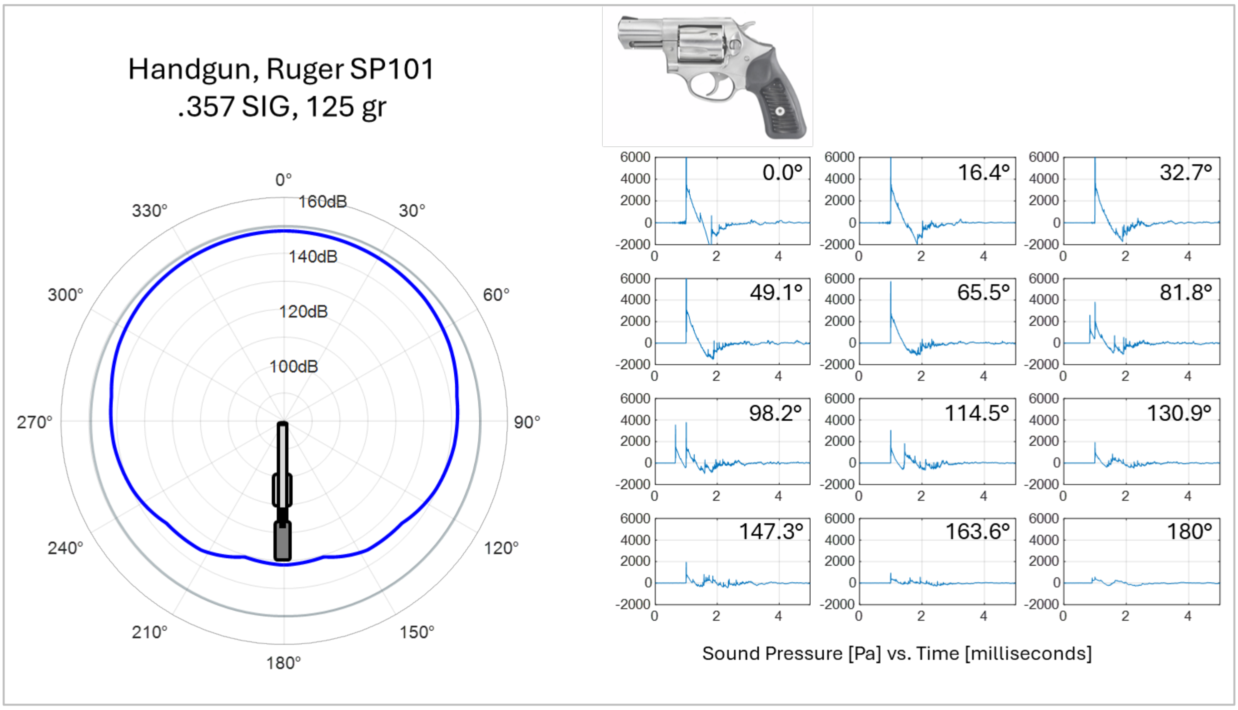

Figure 13: Sound level directional pattern and recordings for Ruger SP101 .357 handgun (front/back diff 6 dB) Note that sound impulse emanating from the cylinder gap of the revolver is observed for the recordings with azimuths wider than 81.8°, giving a double impulse [11].

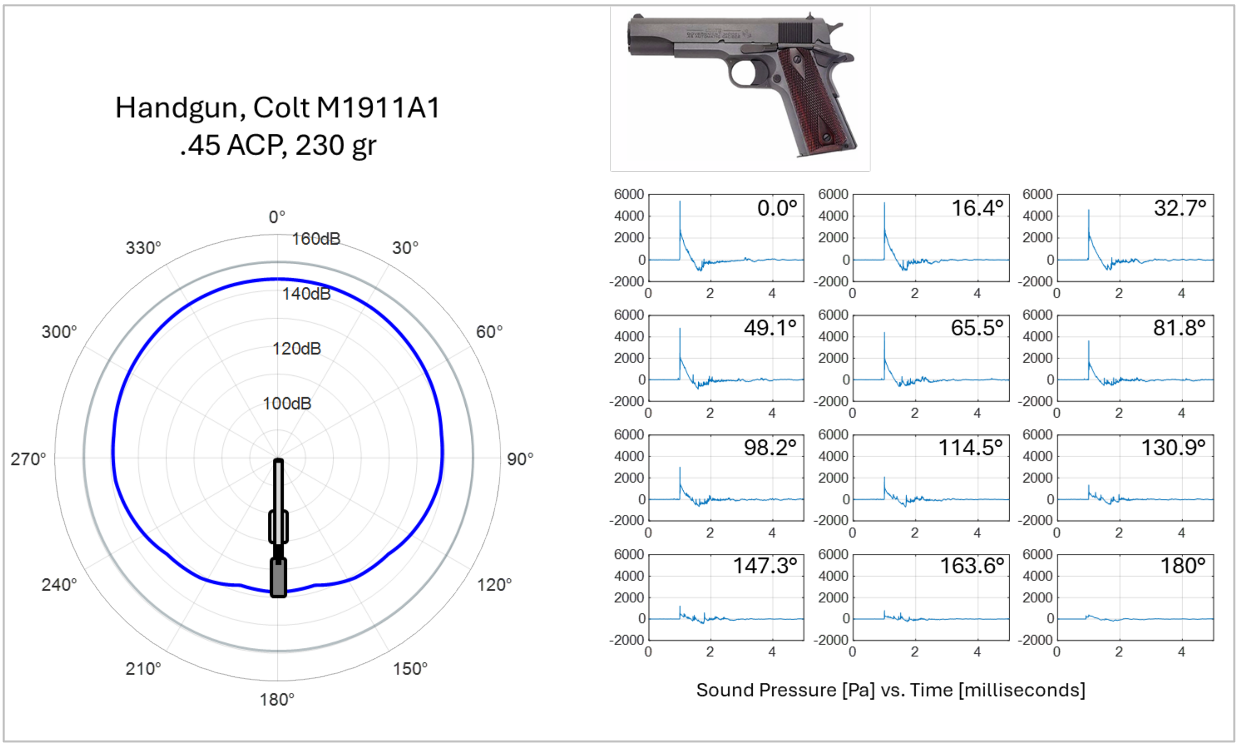

Figure 14: Sound level directional pattern and recordings for Colt M1911A1 handgun (front/back diff 12 dB).

The directional sound level patterns for four of the firearms are shown together in Figure 15 as an example comparison.

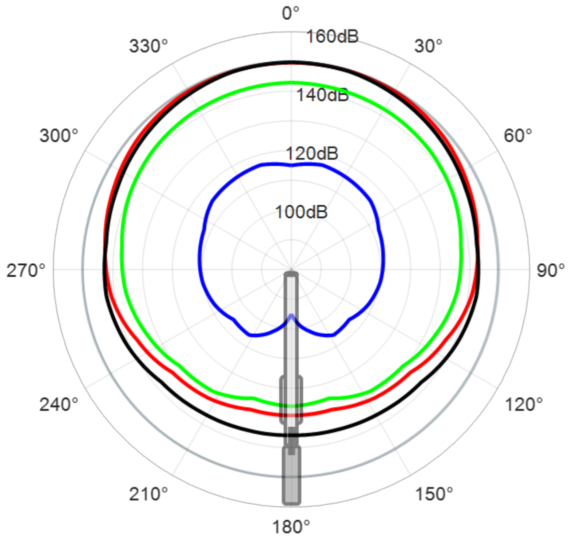

Figure 15: Sound level directional pattern comparison for four firearms: .22 rifle (blue), Glock 19 pistol (green), AR-15 rifle (red), and 12-gauge shotgun (black).

5 Conclusions

The study reported in this paper examines the directional characteristic of several common firearms that may be of interest to audio forensic examiners. The key findings can be summarized as follows.

1. The RMS sound pressure level re 20µPa on-axis for the 10 firearms varies from about 115 dB (RMS pressure 11.2 pascal) for a .22 rifle to about 150 dB (RMS pressure 632.5 pascal) for a .308 rifle, AR-15 rifle, and 12-gauge shotgun.

2. All of the conventional firearms tested produced a muzzle blast that is directional. The sound emanating in the direction the barrel is pointing has an RMS sound pressure level that is found to be as much as 20dB greater than the SPL measured to the rear of the firearm.

3. The waveshape of the muzzle blast often differs significantly as a function of azimuth. A particularly noteworthy example is the distinctive double impulse in acoustic pressure recorded from the revolver handguns off to the side and behind, due to sound emanating from both ends of the gun barrel as the bullet is fired.

4. The testing reported here describes the *anechoic* characteristics of the muzzle blast sounds as a function of azimuth. Actual forensic recordings will inevitably contain the convolution of these directional pressure waves with the acoustical surroundings between the firearm and the microphone: reflections, diffraction, reverberation, and noise [8].

Thus, audio forensic examiners and developers of gunshot detection and classification systems need to avoid oversimplifying the parameters of gunshot audio recordings. This should be a key concern for those developing training sets for machine learning applications.

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