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Measuring recreational firearm noise

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Recreational use of firearms in the United States is commonplace. There are 28 million Americans who consider themselves hunters and 13 million went hunting in 2000. Participation in the shooting sports without the use of properly worn hearing protection, exposes the involved persons to high levels of impulsive noise which may cause hearing loss and/or tinnitus (ear ringing). The present study was initiated to gain a better understanding of the noise exposure created by contemporary firearms using state of the art instrumentation and to ultimately increase our knowledge and awareness of this unique noise hazard. The sound pressure signal created by recreational firearms as used in hunting or target practice is characterized by a high frequency, short duration impulsive noise. This signal is perceived by the human ear as one single, loud impulse or "shot". However, when the firearm sound level is measured with microphones capable of sampling wide frequency ranges and combined with high speed data acquisition computer systems, the impulses can be resolved into a number of different acoustic signals related to different source mechanisms.

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1 INTRODUCTION

Recreational use of firearms in the United States is commonplace. It is estimated that approximately one-third of households in the U.S. own firearms (Johnson, Coyne-Beasley, & Runyan, 2004). There are 28 million Americans who consider themselves hunters and 13 million went hunting in 2000 (U.S. FWS, 2001). Participation in the shooting sports without the use of properly worn hearing protection, exposes the involved persons to high levels of impulsive noise which may cause hearing loss and/or tinnitus (ear ringing).. Firearms may cause permanent hearing loss even after a single or a few unprotected exposures. The present study was initiated to gain a better understanding of the noise exposure created by contemporary firearms using state of the art instrumentation and to ultimately increase our knowledge and awareness of this unique noise hazard.

The sound pressure signal created by recreational firearms as used in hunting or target practice is characterized by a high frequency, short duration impulsive noise. This signal is perceived by the human ear as one single, loud impulse or "shot". However, when the firearm sound level is measured with microphones capable of sampling wide frequency ranges and combined with high speed data acquisition computer systems, the impulses can be resolved into a number of different acoustic signals related to different source mechanisms. The acoustic characteristics of firearm impulse noise put great demands on the instrumentation. Therefore, the transducers and the data acquisition system are critical, especially in terms of the dynamic range, frequency response, slew rate and sampling rate, all of which need to be carefully considered.

The present study focuses primarily on recreational firearms as a noise source and considers the acoustic interaction of the resulting sound field with the human head. It does not delve into the potential auditory damage experienced by an individual shooter or extend to discussions of specific auditory risk criteria.

2 MEASUREMENT PROCEDURE

2.1 Microphone selection

The typical signal from recreational firearms is a short impulse with an extremely brief rise-time and a high crest factor. The peak level of the signal will be dependent upon the physical distance from the firearm and the azimuth relative to the end of the barrel (muzzle). In general, levels of more than 140 dB SPL_{peak} should be expected and may vary as a function of ammunition. Figure 1 illustrates the inverse relationship between microphone sensitivity and dynamic range (rms). It is apparent that a lower microphone sensitivity allows handling of greater sound pressure levels (SPLs. For the present measurements, an 1/8" microphone type 40DP with sensitivity of 1 mV/Pa was selected, thereby providing a dynamic range (peak capability) of approximately 45-186 dB (3.5 mPa to 40,000 Pa).

In the frequency domain the short acoustic impulse corresponds to a broadband signal with very high frequency content. It is therefore important that the microphone has sufficient bandwidth to capture the signal. It is also important that the transducer is small compared to the wavelength of the target sound at the high frequencies. As the dimension of the transducer (diameter) becomes comparable to the wavelength, the microphone will start to change the sound field locally around the microphone. If the microphone is pointed towards the direction of the propagation (0° incidence) of the sound field as in Figure 2, the presence of the microphone in the sound field will cause diffraction around the microphone and will result in an increased sound pressure gradient in front of the microphone.

The diffraction effects can be minimized by pointing the microphone perpendicular to the direction of sound propagation (90º incidence), as illustrated in Figure 3. This orientation will not cause the pressure build-up in front of the microphone as the sound wave will simply pass over the diaphragm unaltered. However, a 90º incidence placement will limit the useful frequency range of the microphone. As the wave length becomes shorter at higher frequencies, different parts of the microphone diaphragm will be subjected to different pressures. In the extreme case where the diaphragm diameter equals the wavelength (as in Figure 3), half of the diaphragm will be subjected to negative pressure and the other half to an equivalent positive pressure. This results in an average pressure over the total diaphragm surface of zero, and consequently a microphone output signal of zero. In reality, the reduction of the output signal starts at lower frequencies than the frequency where the wavelength is equal to the diameter of the transducer. For the 1/8" microphone type 40DP, the cut-off frequency is around 80 kHz.

2.2 Preamplifier selection

Preamplifier considerations included the ability to handle the output signal from the microphone without overloading, the slew rate limitation and the capacitive loading from cables connecting the preamplifier to the subsequent data acquisition system.

For an excitation of 40,000 Pa at the microphone with a microphone sensitivity of 1 mV/Pa, the output signal from the microphone will be 40 V. This means that the preamplifier will have to be able to handle an input signal of at least 40 V and thus that the supply voltage to the preamplifier should be no less than ±40V. In this case, a type 26AC preamplifier was driven by a GRAS type 12AA Power Module generating a ±60 V supply voltage enabling the preamplifier to handle signals up to ± 60,000 Pa (189.5 dB SPL_{peak}). The 12AA power module included a 20 dB attenuation so that the output signal from the preamplifier could be reduced as necessary to fit the dynamic range of the subsequent data acquisition system.

2.3 Data acquisition system

A National Instruments PXI-6120 simultaneous sampling data acquisition board mounted in a 4-slot PXI chassis was used for A/D conversion. This board allowed four data channels to be recorded with sampling rates up to 800 kHz with an analog trigger facility. The data was stored in a 64 MSample on-board data buffer, and was set-up to record 50 ms of data before the trigger with a total data length of 0.5 s. The data were sampled with 16 bit resolution giving a 90 dB dynamic range. The data acquisition was controlled by a custom LabView program with integrated calibration routines and trigger control and the data were afterwards post-processed with National Instruments Diadem.

2.4 Experimental set-up

A series of acoustic measurements were performed outside on a grass surface with no other major surfaces creating reflections within the time frame of interest. In order to test the firearm without the shooter present, the firearm was mounted in a test fixture and fired remotely except when the shooter's head was present for the recording. The set-up as shown in figure 4 includes

4 channels of 1/8” microphones with ¼” preamplifiers with two power modules type 12AA. Microphones were oriented at grazing incidence to the wave front.

3 THE FIRNG PROCESS

3.1 Impulse at shooters position

The firing of a recreational firearm, like a rifle, may be described by the following chain of events: the trigger is pulled and the firing pin hits the cartridge. This ignites the primer, which then ignites the powder. As the powder combusts and expands, the bullet is accelerated through the barrel until it exits the muzzle. The bullet will travel forward, usually at supersonic speed, which produces a conical shock wave, often called a sonic boom, which expands backward from the bullet tip. In addition, a spherical blast wave centered on the muzzle will be produced at the moment that the hot compressed gases are released. Finally, the gases containing combustion by-products will produce turbulent airflow around and in front of the muzzle as it is carried forward by momentum and cools. Figure 5 illustrates a typical time-based signal for a .22 Hornet Winchester Model 43 rifle with factory ammunition. The signal was recorded with a microphone at a position where a shooter would normally have his/her head, but without a human actually present in the sound field.

The acoustic signal in Figure 5 is dominated by a peak of approximately 1000 Pa (~154 dB SPL_{peak}) occurring at t=1 ms. Closer inspection of the signal reveals another signal 3 ms before this major peak, (Figure 6). It is apparent that the microphone at the head position starts to pick up an earlier signal, although at a much lower amplitude. This early signal is generated when the trigger is pulled. About 1 ms after triggering the firearm, the powder combusts and the noise burst is emitted directly from the cartridge *through* the rifle structure to the microphone outside the firearm. Due to the attenuation of the signal by the rifle structure, the signal strength is relatively low, with peak values around 30 Pa or approximately 123 dB SPL_{peak}. The noise generation then continues while the bullet travels through the barrel.

The barrel of the .22 Hornet Winchester has an effective length of 0.5 m. If the average bullet speed through the barrel is assumed to be around 700 m/s, the bullet will exit the barrel approximately 0.7 ms after combustion. As the bullet exits the barrel, a pressure wave will follow the bullet and will be transmitted from the muzzle back to the microphone position. Initially, the pressure wave will travel faster than the speed of sound but this will quickly be reduced to a radiation velocity at the speed of sound. It will then take the sound wave approximately 1.4 ms to travel the 0.5 m distance from the muzzle back to the microphone position. The 1.4 ms wave travel time plus the 0.7 ms bullet travel gives a total delay of 2.1 ms from the cartridge ignition until the blast wave from the muzzle is received by the microphone.

3.2 Impulse at muzzle position

Inspection of the signal obtained near the muzzle as in the red curve in Figure 7, reveals a peak level much higher due to the closer proximity to the sound source. At the muzzle, the signal can also be broken down into a number of different peak signals. At the t=0 ms timing mark, a first peak at around 500 Pa (~148 dB SPL_{peak}) is generated by the front of the bullet exiting the barrel. This peak is generated by the air compressed in front of the bullet as it travels through the barrel. When the rear of the bullet has exited the barrel, approximately 0.1 ms later, a second much higher peak of around 4000 Pa (166 dB SPL_{peak}) is generated by the expanding hot gasses from the burning of the cartridge powder.

The peak generated by the expanding gases is repeated after about 0.8 ms. This secondary peak, at around 2000 Pa (160 dB SPL_{peak}) is possibly caused by reflection of the first pressure pulse in the barrel. As the expanding pressure pulse in the barrel reaches the muzzle, the acoustical radiation impedance will change from the impedance in the narrow barrel tube to the free field radiation impedance. This impedance change will generate a reflected wave travelling backwards into the barrel. As this reflected wave reaches the closed cartridge end of the barrel, the wave is again reflected forward within the barrel. This secondarily reflected wave will then reach the muzzle and will again be radiated outwards from the muzzle. Since the gas temperature in the barrel is much higher than outside the barrel, the speed of sound will be higher within the barrel than outside the barrel. Therefore the reflected wave inside the barrel will travel faster than the normal speed of sound of 344 m/s. Calculating backwards from the time it takes the reflected pulse to travel back and forth in the barrel, and assuming the gas in the air as a first approximation to be an ideal gas, the temperature of the gas can be estimated to be around 3000 ºC.

3.3 Impulses in front of muzzle

The sound field in front of the rifle, parallel to the path of the bullet was investigated with four microphones in positions as shown in Figure 8. The red curve, corresponding to the signal from the microphone closest to the muzzle is dominated by a high peak level at around 32,000 Pa (~184 dB SPL_{peak}), followed by a longer, negative pressure wave of around -17,000 Pa. The initial positive pressure peak is transmitted from the first microphone position to the second microphone position, indicated by green, in approximately 0.3 ms. The distance between the two microphone positions (100 mm) can be used to calculate the transmission speed for the peak. The result is approximately 340 m/s, corresponding to the speed of sound.

The negative pressure peak, however, is not transmitted at the speed of sound. It can be seen that it takes this pressure extreme 0.5 ms to travel the 100 mm from the red microphone position to the green position, corresponding to a speed of 200 m/s. The transmission of the negative wave from the green position to the blue position, a distance of 200 mm, takes approximately 1.5 ms, corresponding to a mean velocity of 120 m/s. It is apparent that the propagation speed of the negative wave is decreasing with the distance from the muzzle. This means that the negative pressure pulse is not a sound wave but a bulk movement of air. This can be explained as a volume of hot air being “blown” away from the muzzle and this is being decelerated by the resistance from the ambient air. As the hot air moves away from the muzzle it is cooling down and therefore the pressure constantly drops, resulting in a negative pressure.

At the microphone positions closest to the muzzle, (corresponding to the red and green positions in Figure 8), the supersonic pressure wave generated by the bullet is buried in the initial blast from the expanding gases. Farther away, at the blue and pink microphone positions, the supersonic pressure wave generated by the bullet are clearly separated from the blast wave, see Figure 9.

The bullet pressure wave is visible at t=0.5 ms. This illustrates a typical N-profile of a supersonic boom. This waveform can be seen at time t=1 ms, as the bullet passes the microphone position marked with pink. With a distance between the blue and the pink microphone positions of 400 mm and a time difference of 0.5 ms, the bullet speed can be calculated to 800 m/s, or more than twice the speed of sound. It can also be seen that the blast wave following the bullet is slower, as it takes this approximately 1.2 ms to travel from the blue to the pink microphone position, corresponding to a sound velocity of around 340 m/s.

3.3 Source directivity

Comparing Figures 5 and 8, it becomes evident that the peak level of the blast wave is much higher in the forward direction than in the rearward direction as expected. Figure 10 shows the directionality of the blast wave for three different azimuths relative to the rifle axis.

Figure 10 also illustrates that the lowest sound levels are obtained to the rear of the muzzle where the shooter is typically positioned. Bystanders to the side of the shooter may actually be exposed to higher impulse levels than the shooter. Under normal conditions, persons should never be positioned in front of the muzzle for numerous safety reasons, so the high sound pressure levels generated in this direction may not be of primary concern. However, there are situations where hunting dogs are positioned in front of the hunter when shooting and it should be recognized that the dog is then subjected to much higher levels than what the hunter may personally experience.

3.3 Effect of head in the sound field

As mentioned previously, the measurements presented up to this point were recorded without the head of the shooter present. When the head is introduced, the sound field around the head will be changed by diffraction and shadowing effects. Figure 11 illustrates the measurements recorded from two microphone positions where the shooters ears would normally be located, but without the head actually there. It can be seen that the peak levels at the two “ear” positions are almost equivalent, and that the blast wave reaches the left position (marked with red) slightly before the right (green) position due to the shorter distance from the muzzle.

Figure 12 replicates the measurements made in Figure 11, with the shooter’s head now in the sound field. The pressure for the left “ear” position is increased due to diffraction around the head and closer proximity to the muzzle. At the right “ear” microphone position, the pressure is decreased due to head shadowing effects. The graphic illustrates that the direct path from the muzzle to the right hand side microphone position is blocked by the head and therefore this also reduces the blast wave. So even if the right ear is physically closer to the stock of the firearm, it is the left ear that is exposed to the highest sound pressure level.

4 CONCLUSIONS

The use of sophisticated instrumentation and critical measurement techniques provide an opportunity to explore and quantify the subtle characteristics of impulse signals from firearms. The choice of instrumentation and sampling strategies will impact the measured values and when done correctly, affords an opportunity to learn more about the sound levels experienced by firearm users and/or spectators.

5 REFERENCES

1. Johnson, R. M., Coyne-Beasley, T., & Runyan, C. W. (2004). Firearm ownership and storage practices, U.S. households, 1992-2002. *American Journal of Preventive Medicine, 27*, 173-182.

2. U.S. Department of the Interior Fish and Wildlife Service; U.S. Department of Commerce; U.S. Census Bureau. (2001). *2001 National Survey of Fishing, Hunting and Wildlife Associated Recreation*.

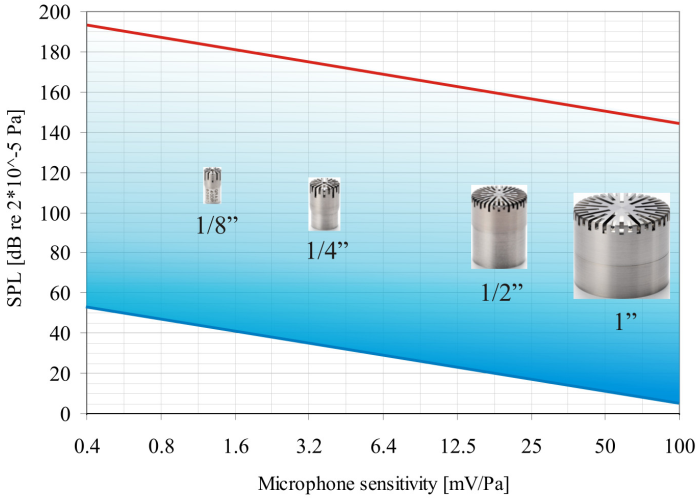

Figure 1. Microphone sensitivity as a function of dynamic range

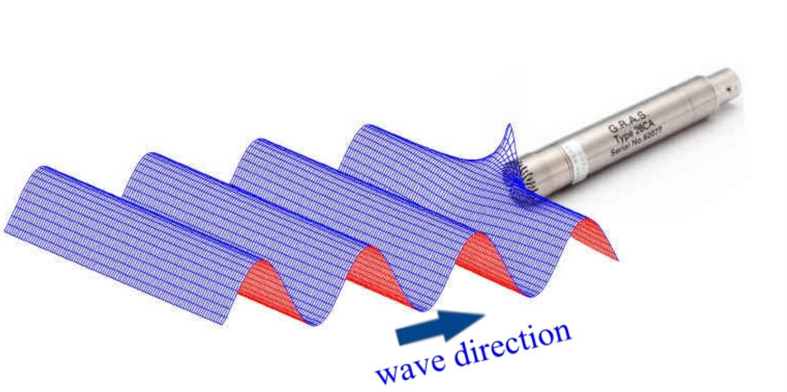

Figure 2. Pressure increase in front of microphone caused by diffraction

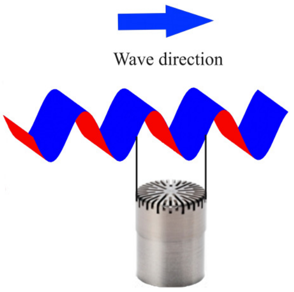

Figure 3. Signal cancelation when wavelength is equal to microphone diameter

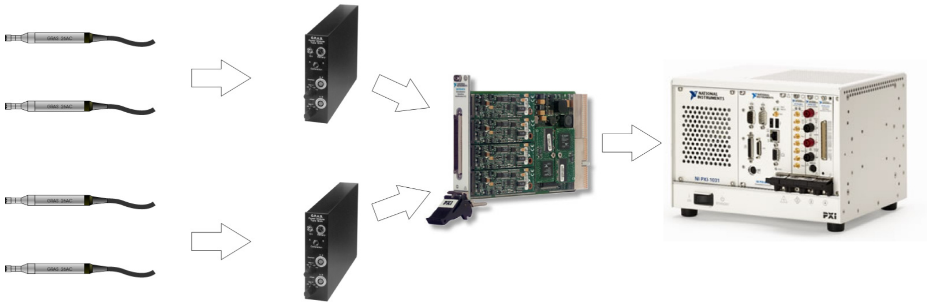

Figure 4. Measurement setup

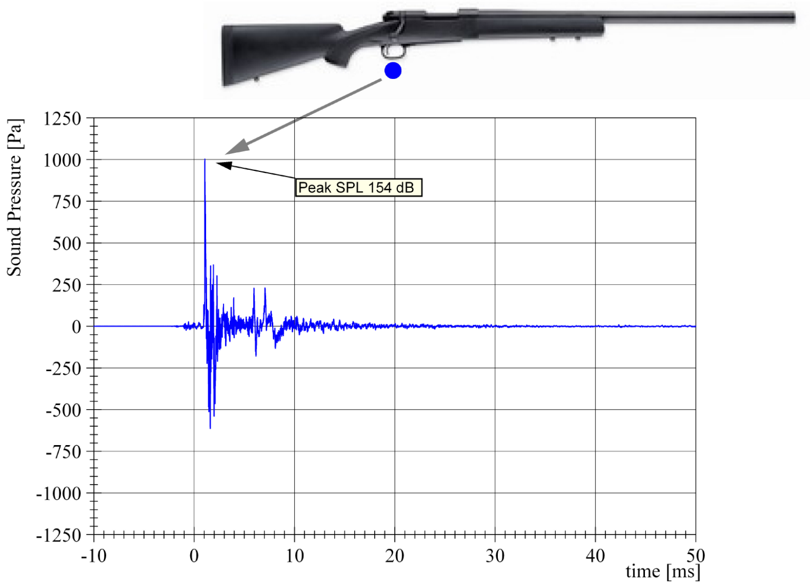

Figure 5. Impulse waveform at the shooter's left ear location (shooter absent) for a .22 Hornet Winchester Model 43 rifle presented in the time domain.

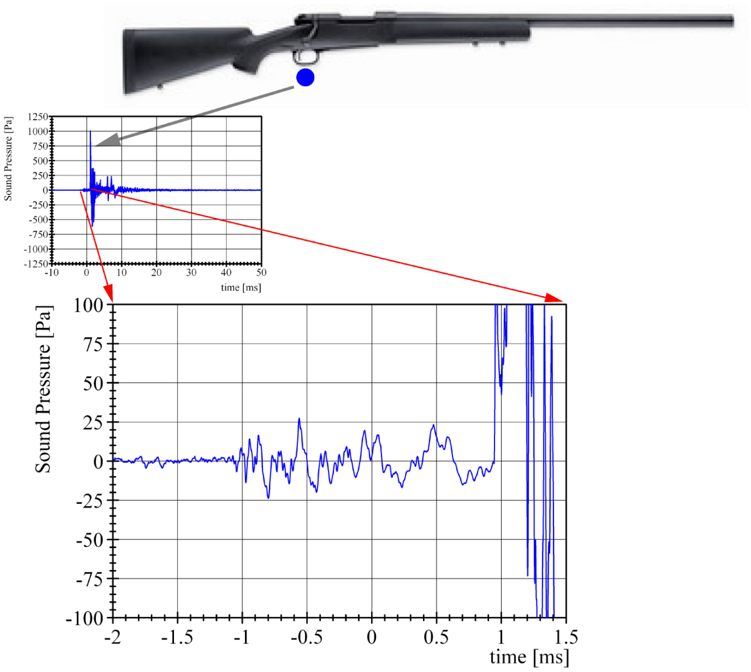

Figure 6. Expanded view of early signal waveform from Figure 5 (.22 Hornet Winchester Model 43). The early disturbance at t=-2 ms to t=-1.5 ms is the sound of the trigger pull, and the sound of powder combustion and bullet travel through the rifle structure is observed between t=-1 ms and t=1 ms.

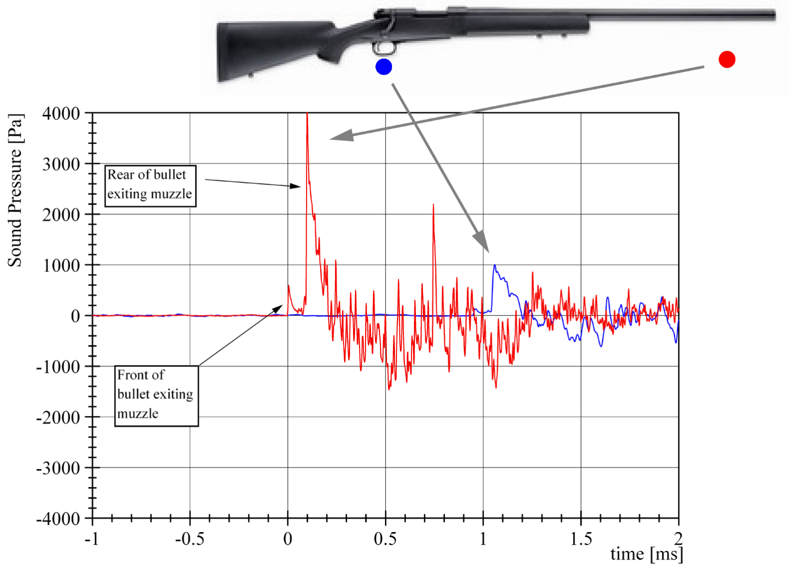

Figure 7. Time domain waveforms of .22 Hornet Winchester Model 43 recorded from two microphone locations. Blue tracing is from the shooter's head location (≈ 154 dB SPL_{peak}) and the red tracing is 250 mm behind the muzzle location (≈ 166 dB SPL_{peak}).

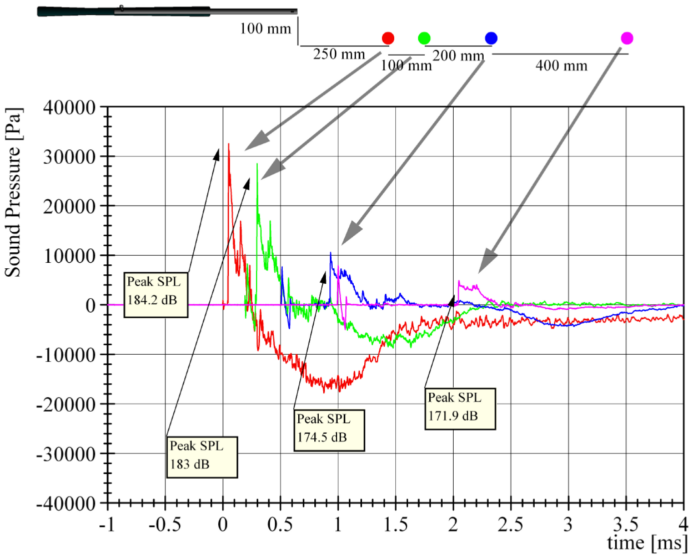

Figure 8. Time domain waveforms of .22 Hornet Winchester Model 43 recorded from four microphone locations. The color corresponds to the microphone location in relation to the firearm. Near the muzzle, the negative peak pressure travels slower than the speed of sound, presumably due to the cooling of propellant gases after they escape the barrel.

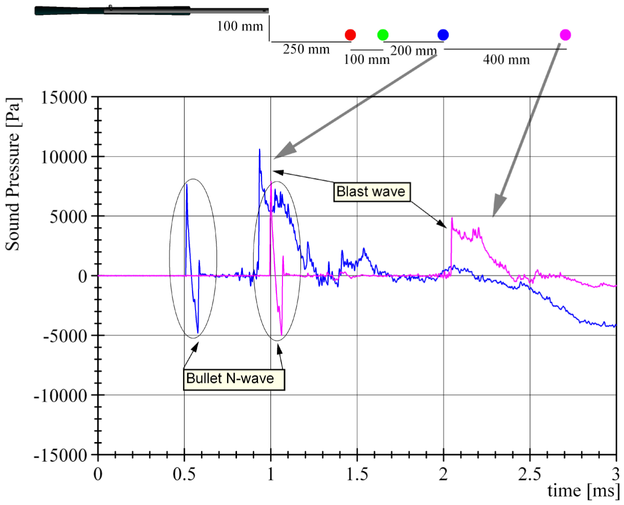

Figure 9: Isolated time domain waveforms for .22 Hornet Winchester Model 43, measured at two locations. The initial N-shaped wave is the supersonic pressure wave (sonic boom) produced by the bullet, the impulse that follows is the shock wave caused by the release of propellant gases. The supersonic pressure wave interval suggests that the bullet was traveling 800 m/s. The shock wave interval is consistent with the speed of sound.

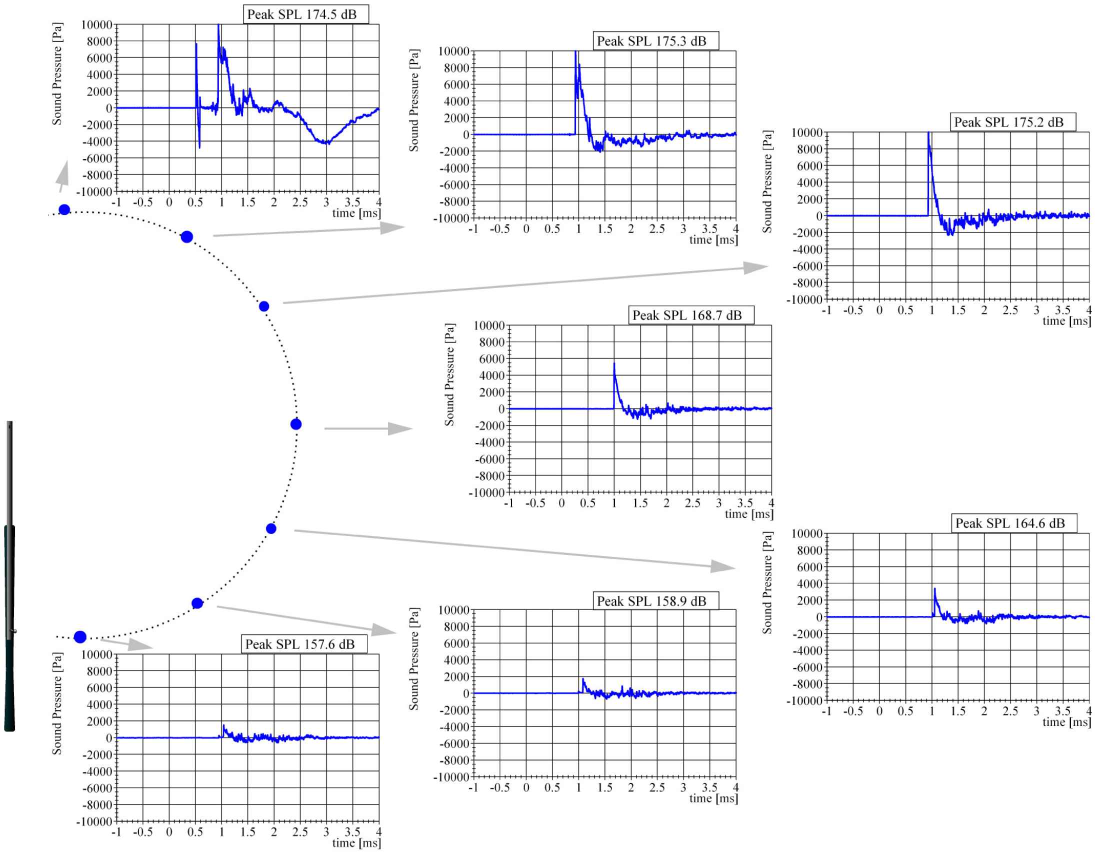

Figure 10. Time domain waveforms as a function of microphone azimuth relative to the axis of a .22 Hornet Winchester Model 43 rifle.

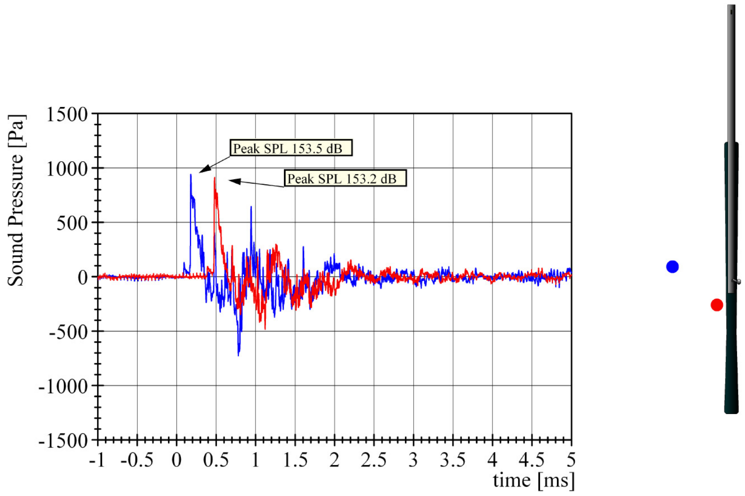

Figure 11. .22 Hornet Winchester Model 43 time domain waveforms recorded at the locations of the shooter's right and left ears (shooter absent).

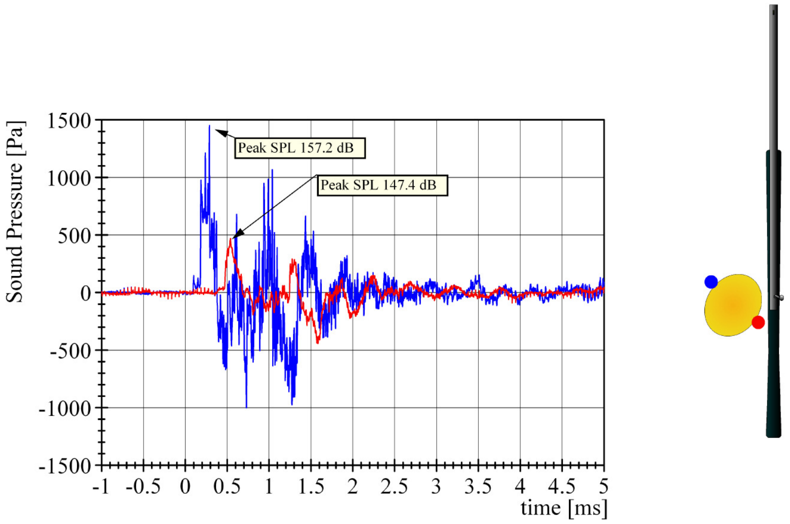

Figure 12. .22 Hornet Winchester Model 43 time domain waveforms recorded from microphone at the locations of the shooter's right and left ears (shooter present).