

Quick Acoustic Analysis of Volley 5, 3rd Burst Front Row – Center Stage

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<https://github.com/Vegas-Oct-1-Sounds/Gunshot-Acoustics>

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Table of Contents

Introduction.....	3
Background.....	3
Tools.....	3
Video Source.....	4
Listen.....	5
Waveform (plot of signal amplitude v. time).....	5
Spectrogram – Db^2 (a measure of energy).....	6
Spectrogram – Log Frequency v Time.....	7
Spectral Contrast Color Plot.....	8
Muzzle Wave Data.....	9
Shock Wave Data.....	11
Lag Calculations.....	12
Multiple Lag Measurements.....	13
General Questions & Observations.....	14
Summary.....	15
Appendix – A – Wisdom from Gunshot Acoustic Theory.....	17
Bibliography.....	19

Table of Figures

Figure 1: Source Location.....	4
Figure 2: Signal Amplitude v. Time.....	5
Figure 3: Power Spectrum.....	6
Figure 4: Log Frequency v. Time.....	7
Figure 5: Spectral Contrast v Time.....	8
Figure 6: Multiple Lag Measurements, Lag v Longitude/Latitude.....	13

Index of Tables

Table 1: Muzzle Waves Timing & Properties.....	9
Table 2: Supersonic Shock Wave(s) Timing & Properties.....	11
Table 3: Lags & Properties.....	12

Introduction

This paper presents a simple acoustical analysis of one part of a volley of gunshots. Purposely little math or technical jargon is used, just enough to present the observations and introduce the reader to a portion of the tools and techniques used in acoustic gunshot analysis. Presented will be:

- audio waveform analysis
- plot of power distribution vs. time decomposed by frequency
- plot of frequency vs. time (frequency on logarithmic scale)
- plot of spectral contrast vs. time
- determination of duration, timing between rounds, r.p.m. of muzzle blasts
- determination of “lag” between the time of arrival of shock wave(s) and muzzle blast(s)
- simple timing characteristics of shock waves
- observations/interpretation of data

Background

Numerous sources explain the theory and application of gunshot acoustics (1–17),(1) In particular dozens, of papers, many not referenced here, authored by Robert C. Mayer Ph.D.,P.E. are available at his [offical University of Montana site](#). The possible sounds generated by gunfire are:

- muzzle blast wave
- one to four shock wave(s) from supersonic projectile(s)
- reflections (ground or otherwise) from muzzle
- reflections (ground or otherwise) from shock waves
- projectile impact sounds
- ricochet sounds
- “whistling” from sub-sonic projectiles
- shell casings hitting a surface
- noises from weapon mechanics

This analysis presents only the muzzle blast(s) and first supersonic shock wavefront(s) for a single eight round burst of gunfire. This burst is the 3rd burst of volley five, occurring approximately at 10:09:55 PM.

Tools

Waveforms and spectrograms were created with [Sonic Visualiser](#). Graphs were created using the matplotlib in Python. Numpy and SciPy python libraries for numerical analysis. LibreOffice for presentation and worksheets.

Video Source

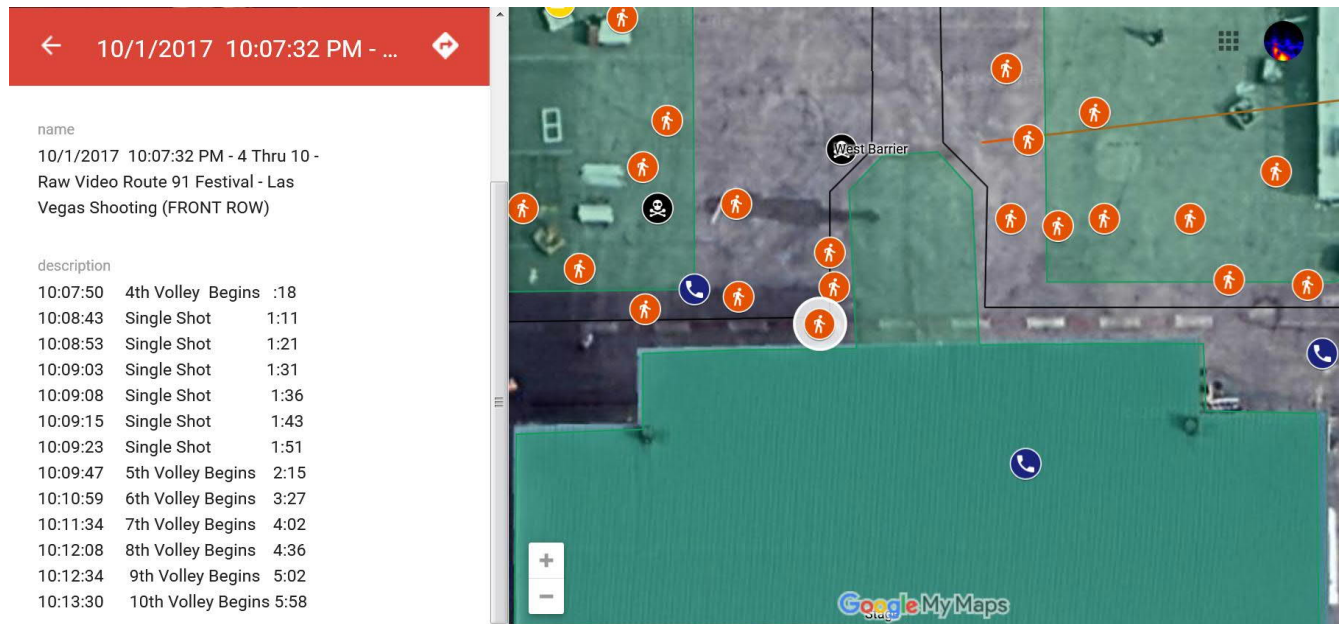


Figure 1: Source Location

The above image was taken from the [Vegas Shooting Map](#) project showing the location where the video was filmed as a highlighted red dot. The location is very near the front row of the stage in the middle adjacent to some wooden lattice.

The full video is located at:

<https://youtu.be/l-IEme0aGMA>

From this full video a 1.37 second segment beginning at 2:23.05 is considered. This is the 3rd burst of volley 5.

Listen

The first step after determining the context of the audio is listening, to identify regions of interest. In this audio clip I hear about twelve distinct “sounds”. The first sounds are like a “snap” or “crack” while the later ones are more similar to a “boom” or “thud”. In the middle of those two groups are sounds with a bit more robustness to them than the snap like sounds. I also hear screaming in the background and a siren. All gunshot like sounds are very audible over the background noise. Both the “crack” like sounds and the “thud” like sounds are quite “loud”, with perhaps the “crack” like sounds a little louder, particularly near the middle of the clip. The first few shots are not as “regular” in cadence as the final four shots. The first few shots contain higher frequencies than the last four. The siren sounds distant, the screams sound closer than the siren.

Waveform (plot of signal amplitude v. time)

After listening to the extracted audio segment, several graphical plots are constructed. The first is a waveform plot consisting of signal amplitude plotted against time.

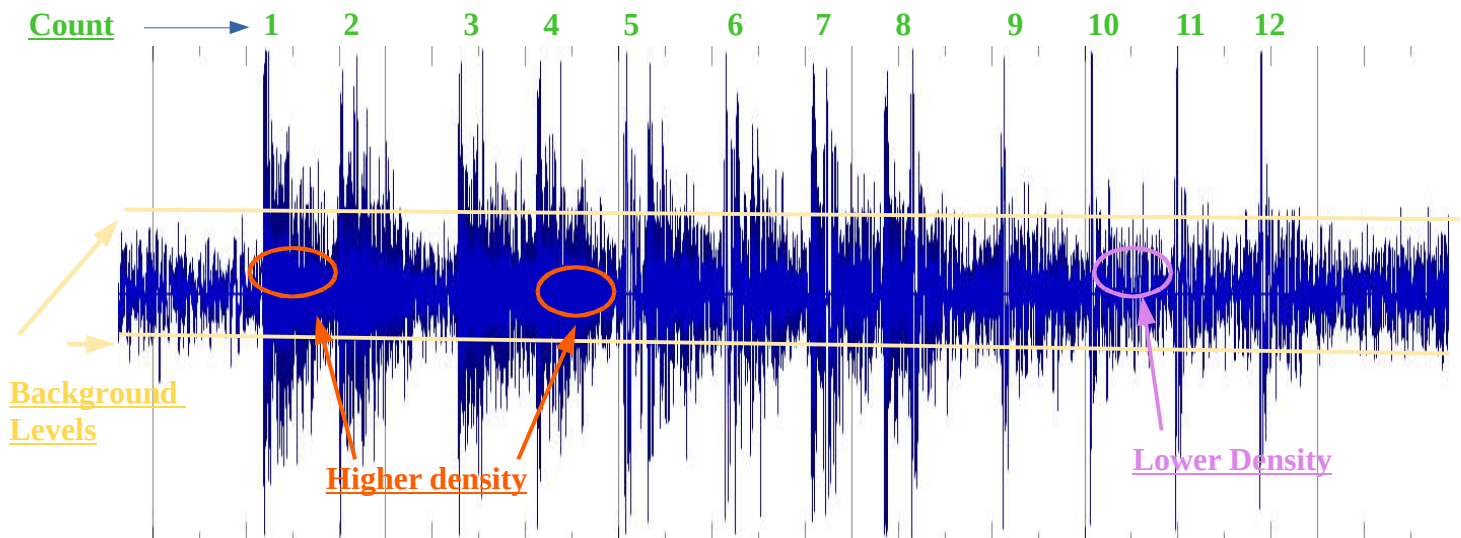


Figure 2: Signal Amplitude v. Time

Observations:

- possible 12 – 16 total pulses.
- possible 8 pulses starting from end of segment that are fairly narrow in scope.
- 8 wide/noisy pulses at start of segment
- 3 or 4 of the narrow pulses overlap with earlier “wider” pulses
- most pulses are larger in amplitude than background sounds.
- Spacing between narrow pulses more regular than spacing between wider pulses.

Spectrogram – Db² (a measure of energy)

From waveform plot we graduate to spectrograms for more detailed analysis. Spectrograms come in many flavors, the first shown below is a plot of energy distribution in the form of frequency versus time plot where energy density is displayed as ever increasing brightness of color. Both frequency and time are plotted on linear scales.

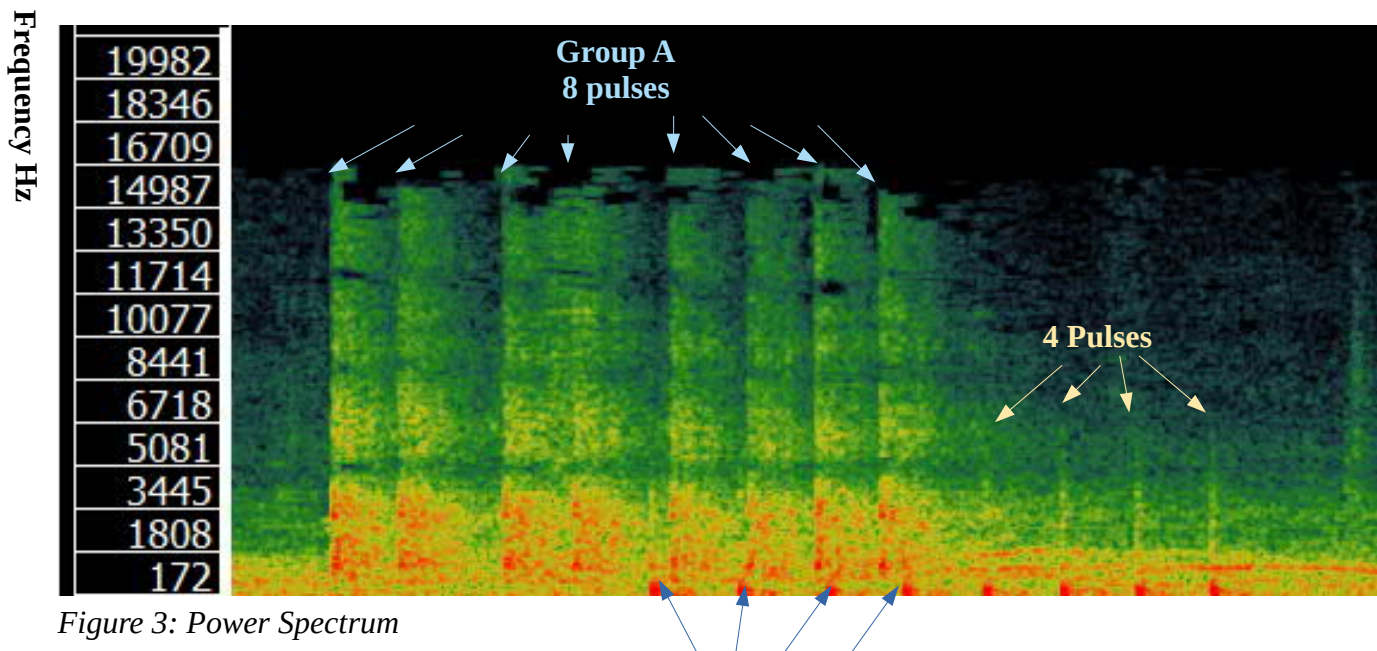


Figure 3: Power Spectrum

Observations:

- at least 12 distinct pulses
- two unique frequency groups
- first 8 pulses (group A) are broadband and have their energy spread over a large range of frequencies.
- First 8 pulses are spread (smeared/fuzzy) over time.
- Last 4 pulses (group B) much narrower frequency band (shorter up and down)
- Last 4 pulses more confined over time (narrower pulse, wider left and right)
- close examination (large magnification) suggest 4 more pulses buried within the first 8 that are similar to last 4 bringing total to possible 16 total pulses.

Spectrogram – Log Frequency v Time

While a power spectrum like Db^2 is good at revealing major events, the linear scale used for frequency masks many of the details. Changing the frequency scale to logarithmic permits closer examination of the lower frequencies. Also changed is the color scale for easy identification, green spectrograms are power, blue coloring is frequency with logarithmic scale. Most muzzle sounds, talking, sirens, and other sounds are easier to examine with the logarithmic scale than a linear scale as the majority of sounds occur below 2,500 Hz.

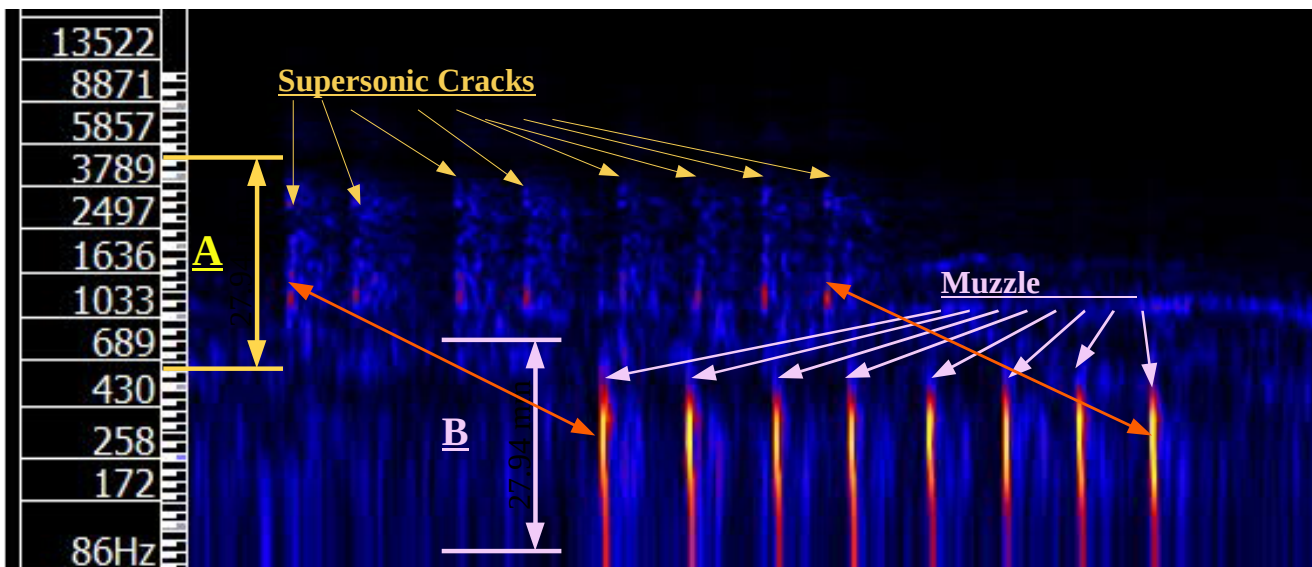


Figure 4: Log Frequency v. Time

Observations

- Supersonic “Cracks” – sonic shock wavefront
 - 8 pulses in group A (upper frequencies)
 - group A consistent with theory predicted frequencies
 - Cracks (A) centered between 3,789-450 Hz
 - wave/sound smeared over time producing fuzzy delineation
 - possible indirect path of propagation
 - irregular timing between rounds
- Muzzle blast wavefront
 - 8 pulses in group B (lower frequencies)
 - group B consistent with theory predicted frequencies
 - Muzzle (B) centered between 689-86 Hz.
 - Fairly regular timing between rounds, near 0.nnn secs
 - some overlap in frequencies between two groups

- “red” lines indicate “lag” between arrival of supersonic “Crack” sound and arrival of muzzle wave sound.
- For “Cracks” 5,6,7,8, the arrival of muzzle events 1,2,3,4 occur close to each accordingly and will be heard as 4 single events due to the limitations of the hearing process, but which can be distinguished separately at slower playback speeds. Each of these 4 events will have a “richer” / “fuller” sound than either the “Crack” alone or the muzzle alone. This phenomena leads to a total of 12 sounds “heard” while listening to the recorded audio.
- In listening, the “volume” of the cracks seems to be about the same as the booms, with the difference given to the cracks.

Spectral Contrast Color Plot

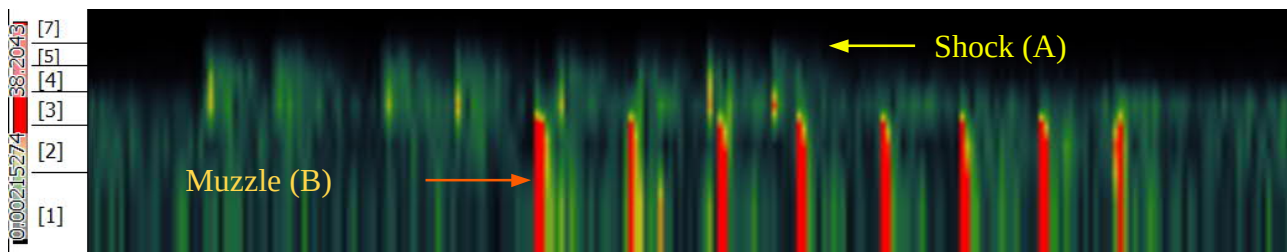


Figure 5: Spectral Contrast v Time

Observations:

- spectral contrast confirms and preserves groups A and B from log frequency plot.
- Group A – Shock waves
 - 8 weaker pulses in bands 3 and 4.
 - contrast with background noise weak, most likely due to “smearing” of energy
 - still 8 pulses, but of varying contrast, may indicate substantial trajectory deviations for rounds 2,3, and 6
- Group B – Muzzle
 - 8 strong pulses in the band 1 and 2

Muzzle Wave Data

An “instants” layer in Sonic Visualizer was overlay-ed with the frequency plot and the beginning of all onsets were marked. The video times below are taken directly from that instants layer with no modification. In marking the locations of each pulse care was taken to minimize the error to 2 milliseconds.

Table 1: Muzzle Waves Timing & Properties

<u>Shot No.</u>	<u>Vid. Time</u>	<u>Delta</u>	<u>Delta Delta</u>	<u>R.P.M.</u>	<u>Delta - Mean</u>
1	143.505215420				
2	143.612698413	0.1075		558.23	
3	143.719954649	0.1073	-0.000227	559.41	
4	143.812925170	0.0930	-0.014285	645.37	
5	143.909297052	0.0964	0.003401	622.59	
6	144.004535147	0.0952	-0.001134	630.00	
7	144.095011338	0.0905	-0.004762	663.16	
8	144.186621315	<u>0.0916</u>	<u>0.001134</u>	<u>654.95</u>	
Avg.		0.0973	0.003120	619.10	

“**Vid. Time**” are all relative to the beginning of the video. From there the differences between each pulse of sound was calculated and entered in to the **Delta** column. This column provides the time between shots. The average was 97.3 mili-seconds. As a crude measure of cyclic rate of fire, this column can be used to calculate revolutions per minute by: $r.p.m. = (1/\Delta) \cdot 60$. The average r.p.m. for these eight shots was 619.

Total duration of muzzle events: 0.680 seconds.

The time between shots is determined by (a) gun firing mechanisms (b) gunpowder in rounds (c) distance between shooter and recorder (c) speed of sound. Changes to any will contribute to difference in timing between shots. In this particular instance, the recording device is stationary, therefore any changes in distance must be solely caused by changes in shooting location.

If the

Assuming the speed of sound for the temperature and elevation that evening was 1,160 feet per second, then every 1/1000 second (mili-second) equates to about 0.8621 feet or every 1.16 mili-seconds equates to 1 foot. Thus if there is time difference between two shot deltas of 11.6 mili-seconds, the shooter would have been required to move that distance in the time it takes to fire between the shots. This can be calculated as roughly 57 mph. Not an easy feat for someone on foot. If in mobile device, this speed is possible only if the mobile device was pulling directly away from the shoot. If the mobile device was pulling away at an oblique angle the speed would have to be increased dramatically to accomplish the task.

Shock Wave Data

Table 2: Supersonic Shock Wave(s) Timing & Properties

<u>Shot</u>	<u>Time Since Start</u>	<u>Delta</u>	<u>Delta Delta</u>		
1	143.117188209				
2	143.199274376	0.0821			
3	143.326666667	0.1274	0.0453		
4	143.411020408	0.0844	-0.0430		
5	143.529591837	0.1186	0.0342		
6	143.622675737	0.0931	-0.0255		
7	143.705668934	0.0830	-0.0101		
8	143.783582766	<u>0.0779</u>	<u>-0.0051</u>		
<u>Avg.</u>		0.0952			

Total duration of shock events: 0.662

Lag Calculations

Table 3: Lags & Properties

<u>Shot</u>	<u>Lag</u>				<u>Lag - Avg.</u>
1	0.388				-0.0040
2	0.411	0.0230			0.0190
3	0.394	-0.0170			0.0020
4	0.400	0.0060			0.0080
5	0.377	-0.0230			-0.0150
6	0.378	0.0010			-0.0140
7	0.389	0.0110			-0.0030
8	0.400	0.0110			0.0080
<u>Avg.</u>	0.392	0.0131			

Multiple Lag Measurements

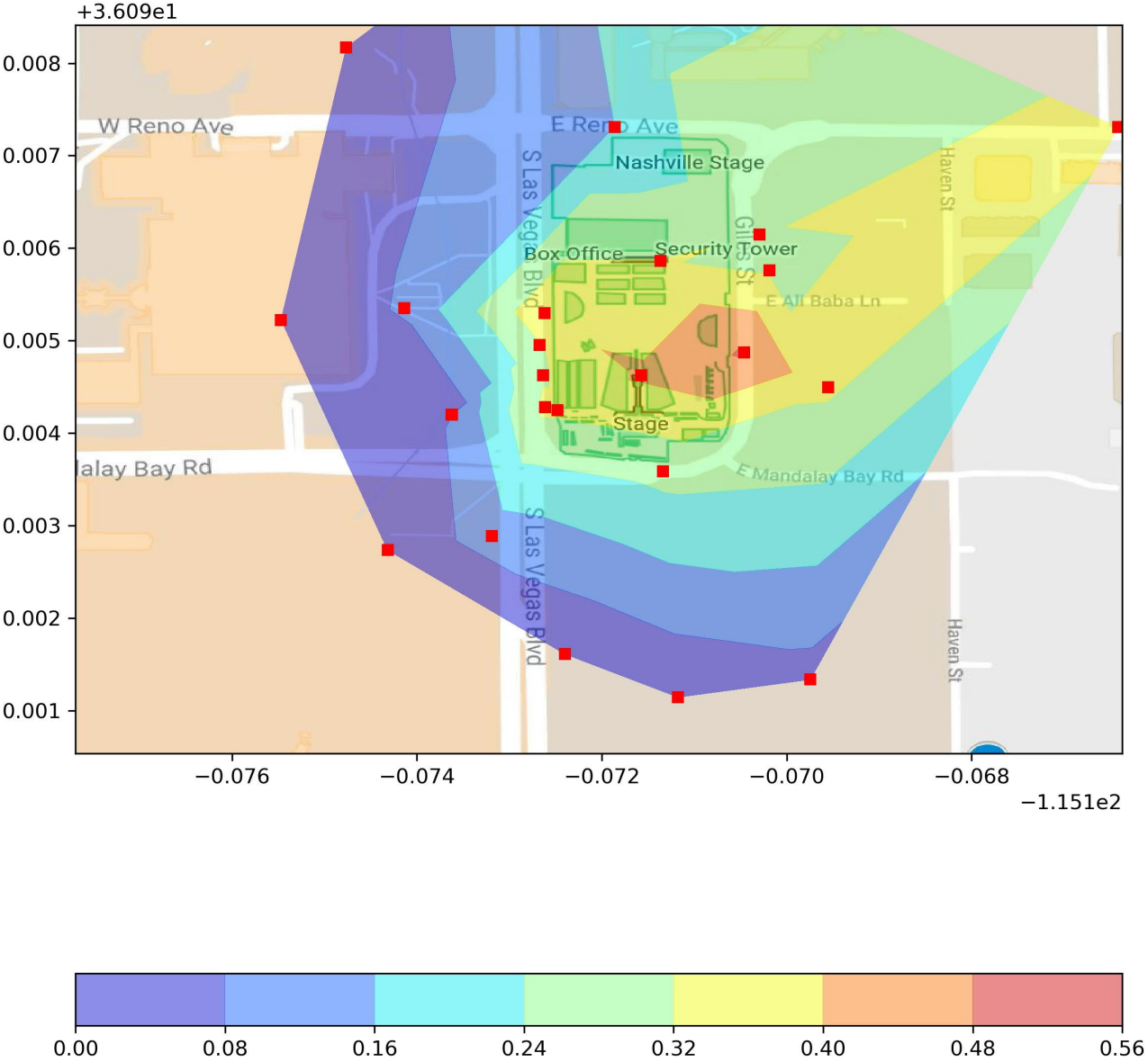


Figure 6: Multiple Lag Measurements, Lag v Longitude/Latitude

General Questions & Observations

1. How do we know these are gunshots?

The same way we recognize a car, from past experiences. That is, numerous well researched and well documented actual gunshots are available. These gunshots are subject to the same analysis done here and provide good matches (a matter for another paper). As well as comparing this set of sounds to known gunshots, this analysis provides characteristics (frequency, duration, power distribution, spectral contrast, waveform, timing) that match acoustic gunshot theory. There are also documented cases of gunshot impact/wounds/deaths in the vicinity of the recorded sounds.

2. How do we know these sounds aren't speaker/lrad/magic device generated?

The strongest argument against an artificial sound source is the variation in "lag" from location to location. That is, if you look at Figure 6, the reader can see that lag varies by location. If a single source of sound imitated a sonic wave followed by a muzzle blast with 0.2 seconds between, then that difference would be recorded as 0.2 seconds for all recording locations. Since it is not, then a single imitation sound source is not the culprit. And if someone want's to argue multiple sound sources, then they had better come up with enough sources to cover hundreds of recordings each with a different lag.

3. The cadence (time between rounds) of the supersonic shock waves is different from the cadence of the muzzle waves. This is quite often the case. Muzzle sound propagation primarily depends on the speed of sound and the distance between the shooter and the recorder (two variables) and if both the shooter and recorder are fixed in location, then the relative time of arrival will remain the same. Shock waves on the other hand are continually generated by the supersonic projectile and the time of arrival for them is primarily dependent on speed of sound, speed of projectile, downrange distance and cross-range "miss" distance (four variables). Thus even if both shooter and recorder remain at the same location between rounds, the shock wave may arrive at different times due to variations in either the bullet speed or bullet trajectory which alters the downrange and/or cross-range distance and/or timing.
4. Count of events in group A matches the count of events in group B. As expected for audio which records both muzzle and shock wave.
5. Lag varies from shot to shot. As would be expected when the bullet does not travel the exact same trajectory/path each round.
6. Frequency range of group A from frequency plot agrees well with theory for supersonic projectile shock wave.

7. Frequency range of group B from frequency plot agrees well with theory for muzzle blast waves.
8. Good frequency separation between groups A and B (shock v muzzle)
9. Supersonic shock wavefront precedes muzzle blast waves as predicted by theory.
10. Existence of supersonic shock wave implies rifle.
11. Existence of relatively large lag implies both substantial distance downrange and relatively small cross-range “miss” distance.
12. Timing of muzzle sounds ambiguous, could be automatic weapon or could be bump-stock. That is, this volley has very regular almost mechanical times between rounds. However this burst should be considered in the general context of all bursts within volley 5 which are less regular in timing. See [Vegas Cyclic Rate & Variance](#) for a more detailed background and why this volley was not produced by a 240 series (belt or magazine fed) machine gun.
13. “lag” consistent with multiple lags measured from multiple videos with multiple volleys all indicating an elevated shooting location in a south westerly direction from the venue.

Summary

To the ear, this segment presents twelve “shots”, closer examination demonstrates that there are only eight shots each producing two sounds, one from the supersonic projectile, and another from the exploding gases exiting the muzzle of the weapon. The supersonic shock wave arrives first, followed some time later by the muzzle sound. In this instance all of these phenomena are quantifiable with the aid of Fourier transforms available via Sonic Visualiser.

Thus a total of sixteen sounds are generated by eight rounds of fire. For this location the time of arrival of the shock wave and the time of arrival of the muzzle wave differ by about **0.392** seconds, which causes the first muzzle sound to arrive at approximately the same time as the fifth shock wave and overlap the next three shock waves (a total of four overlapping). Overall this overlapping extends the apparent length of the burst.

While the ear is good at detection, it is often poor and sometimes misleading about the character of gunshot sounds as demonstrated with this example.

From all this analysis what can be surmised about the weapon, ammunition, shooter, and location of gunfire?

First and foremost this analysis provides real measurements founded on real tools, with a sound basis in known and vetted theory of gunshot acoustics. The tools are available to anyone, the measurements are reproduce able, and the theory behind the analysis is readily available on the net.

Given that a supersonic shock wave is recorded, then the weapon is likely a rifle. Given the rapid rate of fire and low variance of timing between rounds, it's likely a machine gun or some sort of trigger mechanism was used. Based on research presented elsewhere, the probability of machine gun use is lower than bump-fire use.

Smooth evenly spaced muzzle wave arrivals suggest that the distance between the shooter and recorder was fixed. That is, neither was moving significantly.

The relatively large “lag” suggests a distant shooter and relatively close proximity to the bullet path. “lag” variance suggest poor control of muzzle positioning and/or large variations in projectile speed. If ammunition is eliminated as a source of variation in “lag” then very poor control of muzzle positioning is indicated (for example no tripod).

The “smearing” of the shock waves indicates multiple sources of reflections very nearby and/or an indirect path of arrival. Given the relatively large power spectrum, the smear was likely related to local sources of reflection.

Much more information can be coaxed out of this audio sample, but is beyond this simple presentation.

When multiple “lags” are combined and plotted against longitude and latitude as in Figure 6, a clear picture emerges, and this volley from this audio is consistent with that picture; a shooter located in an elevated position in a south west direction from the venue whose shooting location was fixed.

Appendix – A – Wisdom from Gunshot Acoustic Theory

- “The bow wave only propagates forward of the line-of-fire and within the mach angle defined by the bullet's speed.”(18)
- “The noise generated at a small-arms range has two components: the muzzle blast and the sonic boom, bow wave noise generated by the flight of the bullet.”
- “The muzzle blast is caused by the powder charge exploding in the gun chamber and can be modeled as an explosion of some equivalent weight of TNT with some directivity specific to the weapon being fired. Therefore, except for the nonuniform directivity pattern, which will be discussed later, the muzzle blast can be modeled by a simple point source located at the point of fire. This leads to the conclusion that the muzzle blast should propagate in a spherical pattern. ”
- Considering that the energy decays in proportion to the surface area of a sphere, it can be shown that the SEL decays, purely due to geometric spreading, as R^{-2} , where R is the distance from the point of fire to the point of interest. This is equivalent to -6 decibel (dB) per doubling of distance.”
- The bow wave portion of the shot noise is caused by the bullet traveling faster than the speed of sound. As long as the bullet's mach number exceeds 1, a bow wave will be continually produced along the bullet's trajectory.
- The amplitude of this bow wave depends on the geometry and caliber of the bullet, while the direction of propagation relative to the trajectory is determined by the speed of the projectile.
- As shown in Figure 1, a supersonic bullet causes a bow wave with a mach angle α (oa). The bow wave propagates perpendicular to the mach angle, creating a conical spreading pattern (Figure 2). It has been shown that the SEL of the bow wave portion of the gunshot depends on the surface area of this conical shape (Thompson). The SEL decays nonlinearly in the near field, where the pressure is very large. This nonlinear model (Pierce 1989) suggests that the SEL decays in direct proportion to $h^{-3/4}$, where h is the horizontal distance from the bullet trajectory to the point of interest. The distance the bow wave has traveled perpendicular to the mach angle is related to h by $r = h \cos(\alpha)$ [Eq 21]. Consequently, r is directly proportional to h and the SEL decays in the near field in direct proportion to $r^{-3/4}$. This can be stated as -4.5 dB per doubling of distance r. In the far field, and for smaller peak pressures, the SEL decay can be modeled by a linear model that depends solely on the geometrical spreading effects of the conical surface. When this is the case, the SEL decays in proportion to r^{-2} , which is equivalent to -3 dB per doubling of distance.
- The one-third octave analysis of the gun shots showed that the bow wave is centered around the 4 kHz band. The muzzle blast contains much lower frequency energy, with the flat weighted

data centered around 200 Hz and the A-weighted data centered around 250 Hz. Because of the large difference in the main components of spectral energy between the bow wave and the muzzle blast, A-weighting the signal has a very large effect. An A-weighting filter attenuates the muzzle blast fundamental frequency by about 13 dB while it increases the bow wave by about 1 dB. Thus the A-weighting significantly affects comparison of the bow wave and muzzle blast. Both flat and A-weighted data are presented as appropriate; however, only A-weighted data are used for comparison.

- This research showed the spectral data gathered from the small arms fire and identified the bow wave and muzzle blast as the important components. The decay rates of the different components, as observed along the microphone array, were also shown. Considering the geometry of the test setup, the bow wave is the dominant component at all test locations. Along lines that interest the line of fire at angles greater or lesser than the one specifically tested in this research, the bow wave will not be at a maximum. Therefore, along these lines the muzzle blast predominates a distances less than 10,000 m. For example, directly in front of the gun the muzzle blast has a directivity factor of 0 dB and it will predominate within a few hundred meters. The muzzle blast will always predominate in areas along lines that interest the line of fire at angles greater than 90 minus the mach angle (α_c). But the bow wave must be considered if communities are within 10,000 m (10 km) of the firing range and lie along lines that interest the line of fire at an angle less than 90-a.

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