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This paper describes a study conducted at U.S. Marine Corps Base Quantico to determine firing range impulse noise levels and assess noise exposures. Measurements were performed with M16A4 rifles at an outdoor firing range, using a 113-channel array of 6.35 and 3.18 mm microphones that spanned potential locations for both shooters and instructors. Data were acquired using 24-bit cards at a sampling rate of 204.8 kHz. Single weapon measurements were made with and without an occupied range, with a shooter and with a remotely triggered gun stand. In addition, measurements were made with multiple shooters to simulate exposures for a realistic range environment. Results are shown for the various range configurations as a function of angle and distance. Analyses include waveforms, spectra, and peak levels, as well as the 10 ms equivalent level. All measurements met guidelines of the applicable military standard MIL-STD-1474E and the data are shown to be of high fidelity and useful for future in-depth analyses and noise dosage model development.

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1. BACKGROUND

This paper describes a study conducted at U.S. Marine Corps Base Quantico to determine firing range impulse noise levels and assess noise exposures. The purpose of taking these measurements is three-fold with two of the objectives leading into the last. The first objective of this field test was to help characterize the noise of the M16A4 rifle. The second is to gain a better insight in MIL-STD-1474E[7] in order to potentially comment on, or give input when asked, on how the standard could be improved. This leads into the final goal of protecting the marines' hearing. Marshall et al.[1] discovered that during basic training, 12.6% marines experience permanent hearing damage in at least one ear. Their study spanned a three-week period of exposures, meaning that even more damage, or a higher percentage is possible for a longer duration of training. Understanding the weapon's characteristics will lead to better possible hearing protection and a general understanding of how a marine is exposed, especially during basic training. As Murphy et al. W. J. Murphy, and R. L. Tubbs[2] noted, "losses may be a result of exposure to multiple weapons and repeated exposure without proper hearing protection."

Although many groups, such as Coles et al.[3] and Rasmussen et al.[11], have performed level measurements of rifle caliber weapons, the full characteristics of the weapons are unknown. Beck et al.[4] studied variance in small firearms to help physically characterize these weapons, but all that is really known about rifles is that they can reach levels exceeding 160 dB[5,6,12,13].

MIL-STD-1474E[7] is the standard for measuring various high level military noises such as military-type weapons and jet noise. The standard discusses high impulse noise measurements and the required parameters necessary for consistent data acquisition, and points to ANSI S12.7 for supporting requirements for impulse noise[15]. Some of these conditions include: measuring at a 192 kHz or above sampling rate, recording at least five impulses, pre and post-calibrations, and firing the weapons at all typical firing positions. The standard also emphasizes the importance of having microphones at "hearing zones," i.e. locations where a warfighter would be during weapons operations. The data for this experiment included both measurements in accordance with the standards and additional data collection points to allow for further analysis into the standard's guidelines and possible recommendations for optimization or improvement.

2. MEASUREMENT SET-UP

A. MICROPHONES

In July 2017, sound measurements were taken of M16A4 rifles at Quantico Marine Base in Virginia. Microphone locations and configurations were chosen to meet the MIL standard guidelines, ensure data quality, improve measurement efficiency, and help characterize the acoustic source and field. Experience from prior successful tests involving impulses, such as Shaw and Gee's[8] prior characterization work on Gatling guns, Murphy et al.[13] and Rasmussen et al.'s[12] work on recreational firearms, was used to develop an initial framework for the tests performed here. Various 6.35 mm (0.25 in) GRAS pressure and free-field microphones were employed around the range, as well as custom GRAS 3D intensity probes and PCB pencil probes. Microphones were broadband-calibrated with a GRAS 90CA-S2 calibration system at Brigham Young University (BYU) before the test. On the test day, the microphones were field-calibrated before and after the recordings with MIL-STD-1474E.

Figure ***1*** shows a picture of the actual range and gives a spatial description of the setup. This range was not uniformly flat farther from the firing line, and made it difficult to locate all microphones at absolute uniform heights relative to the weapon. When a microphone was meant to mimic an ear position, it was simply positioned at the desired height, relative to the immediately surrounding terrain. Figure ***2*** shows a layout of all the microphones that used in the data acquisition. There were 113 acoustic channels used in the data acquisition, in addition to high-speed and high-resolution video, a chronometer to measure bullet speed, and an IRIG-B time code generator.

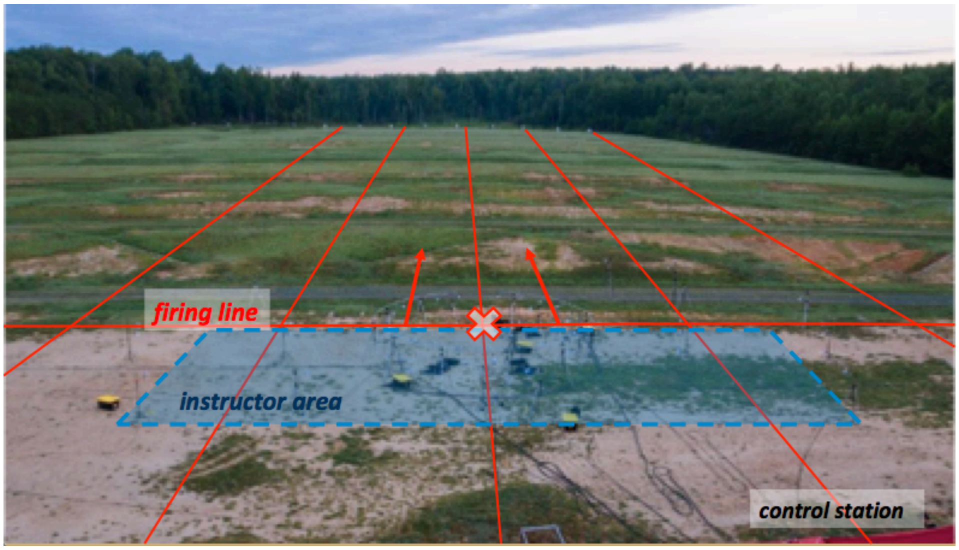

Figure 1. Aerial view of test range.

To help characterize the acoustic source, the measurements went beyond the MIL standard requirements (see Fig. ***2***). For example, a polar arc of microphones with 15° degree interval spacing was designed. This is similar to the data taken by Shaw and Gee for Gatling guns[8], data taken by Vernon et al.9 on exploding acetylene-oxygen balloons, and work done by Roth[12] and Murphy[13] on various firearms. The microphones were mounted on a 4-m radius arc that was fabricated at BYU from pieces of 1” square aluminum and assembled in the field, such that the microphones were located at an effective radius of 3.67 ± 0.02 m from the arc center, with the weapon muzzle located at the arc center ± 0.3 m. In addition to the relatively high-resolution arc, three radials ranging out to 76 m also will help in characterizing the waveform propagation from the source. Lastly, a 16-channel pentaskelion beamforming array was utilized roughly 0.5 m away from the source to determine weapon noise sources, and multiple 3D intensity probes were deployed to localize different events during multishooter, free-firing recordings. This article does not discuss beamforming or other localization results, but these data are a source for future work.

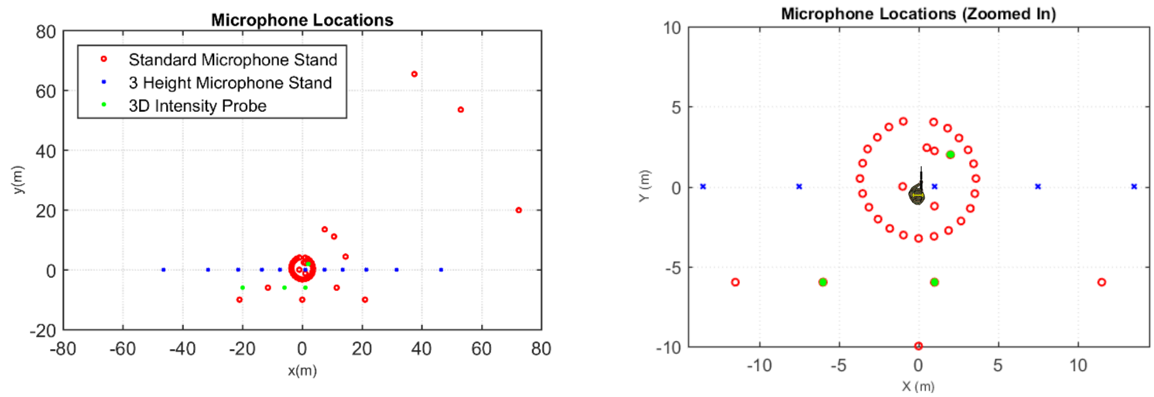

Figure 2. Microphone layout. The right diagram is focused in on the central microphones.

To meet the MIL standard[7] guidelines for assessment of levels at a listener's ear without a listener present (a "hearing zone" measurement)16, two roving microphone stands were employed to gather data at approximate head locations along the firing line ($y = 0$ m). Typically, they would be in positions where shooters would stand along the firing line, generally in increments of 3 m, and were moved in between recordings of different 10-round firings. Note that the weapon's muzzle location was always at approximately $y = 0.5$ m, in front of the lineup. These roving microphone stands allow for an accurate representation for shooter noise exposure due to another shooter's weapon.

Both the roving microphone stands and other microphone stands along the firing line employed microphones at three heights. These "3-height" microphone stands were used to mimic the heights of the shooter in the standing (1.56 m), kneeling (1.09 m) and prone (0.35 m) positions, as seen in Fig. ***3***. While slightly different from the standard7, the heights were selected to better represent the M16A4 Rifle. The microphones at standing height (1.56 m) were pressure microphones oriented skyward, while the rest of the microphones were the free-field type and pointed towards the source.

Figure 3. Example of microphone stand with three different heights. Shooters at three different heights shown at the right.

B. DATA ACQUISITION

In compliance with MIL-STD-1474E, a National Instruments PXIe-1065 chassis with 24-bit PXI-4462 and PXI-4498 data acquisition modules was set to record data at 204.8 kHz, which is above the 192 kHz required. The chassis was connected to an NI-8354 server with solid-state disks in a RAID10 configuration, allowed for consistent, redundant, and accurate data acquisition. Field calibrations and recordings were performed using BYU-designed Acoustic Field Recorder software.

In addition to acoustic data acquisition, two different types of weather stations were employed to record meteorological data for the duration of the test. A Sony RX100 IV camera was used for high-speed video at as high as 1000 frames per second, and two Go-Pro Hero 4 cameras synchronized views of the firing line activity with the acoustic recordings using an IRIG-B time code generator. A chronometer also allowed the team to determine near-muzzle speeds of the supersonic bullets. Bullet speeds were recorded at 950 ± 7 meters per second.

C. SHOOTER CONFIGURATIONS

Over 54 different configurations were tested in order to maximize the analysis available for the M16A4. In Fig. ***3***, one set of conditions (standing, kneeling and prone shooter height) is shown. Also variations in configuration include:

- Occupied range (consisting of one shooter in the center and 12 additional personnel not firing weapons spaced every 3 m to the left and right) vs. unoccupied range (central shooter only).
- Left-handed vs. right-handed shooter.
- Gun stand with a low acoustic profile to eliminate effects of scattering off the shooter's body.
- Marine position either at -18 m, 0 m, or 18 m along the firing line.
- Multiple shooters vs. single shooter.

- Variable locations of roving microphones along the firing line.
- Standing (1.56 m), kneeling (1.09 m) and prone (0.35 m) shooter position, as mentioned.

In each configuration, any shooter would fire 10 rounds of ammunition. At minimum, each recording contains at least 8 impulses, which depended on the communication between shooter and the operator pressing the record button. This is above the threshold of five impulses outlined in MIL-STD-1474E.

3. VERIFICATION AND ANALYSIS

D. WAVEFORM RESULTS

In Fig. ***4***, a pressure waveform is shown for a single impulse from a single right-handed shooter standing at the origin. The microphone is located on the polar arc at 15° from the firing direction. This recording is an excellent example for seeing features of a standard high impulse noise weapon such as the M16A4. The muzzle blast reached peak levels of 162 dB, while the ballistic shock reached 154 dB. Their respective ground reflections also were above the National Institute for Occupational Safety and Health (NIOSH)[17] and DoD[18] recommended 140 dB threshold.

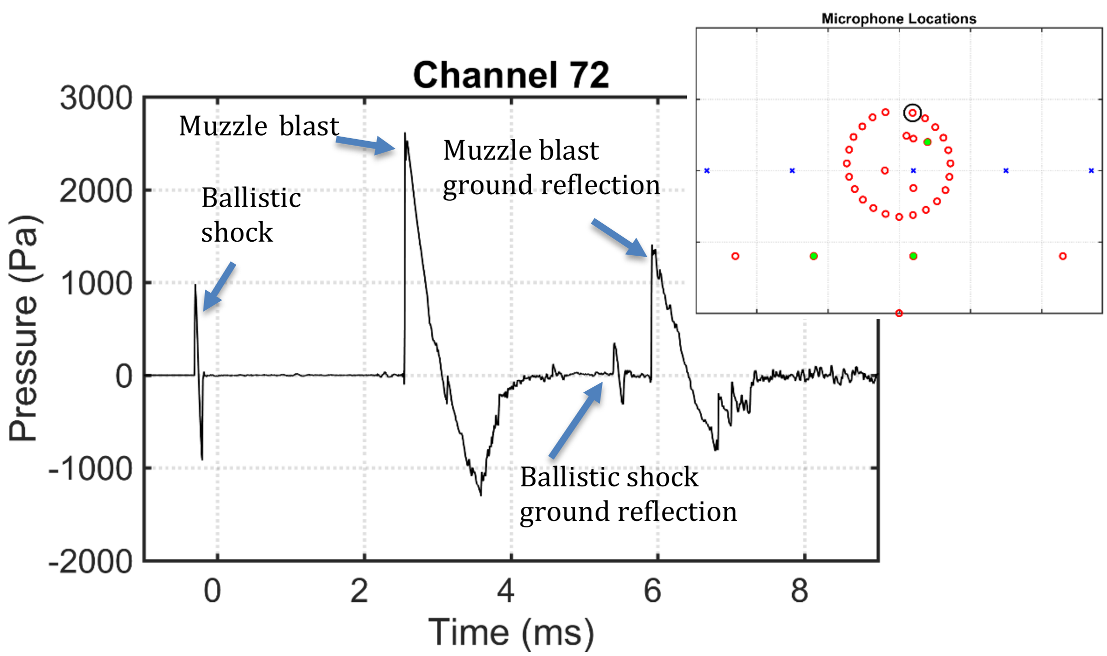

Figure 4. Pressure waveform for a channel for test configuration 11 – Standing right-handed solo shooter standing at the origin. Microphone location shown in top right.

Figure ***5*** shows another pressure waveform of a single impulse from the same shooter, but 90° from the weapon axis. The peak level, 153 dB, is significantly reduced from what is seen in front of the origin, and there is no ballistic shot evident. Figure ***6*** shows the spectrum for the same channel. The spectrum is over 5 seconds of data, or roughly three shots, and has its peak frequency around 650 Hz. The overlaid red curve was created by finding the spectrum from a modified Friedlander waveform and a time-delayed version corresponding to the measurement geometry, with amplitude properties that matched the peak pressure and A-duration of the direct and ground-reflected impulses. The locations in frequency of the first several interference nulls match the geometry, and the measured spectrum matches the high-

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frequency f^{-2} roll-off of the Friedlander spectrum. This roll-off is that expected for an acoustic shock, and confirms the shock-like characteristics of both the direct and reflected impulses in Fig. *5*.

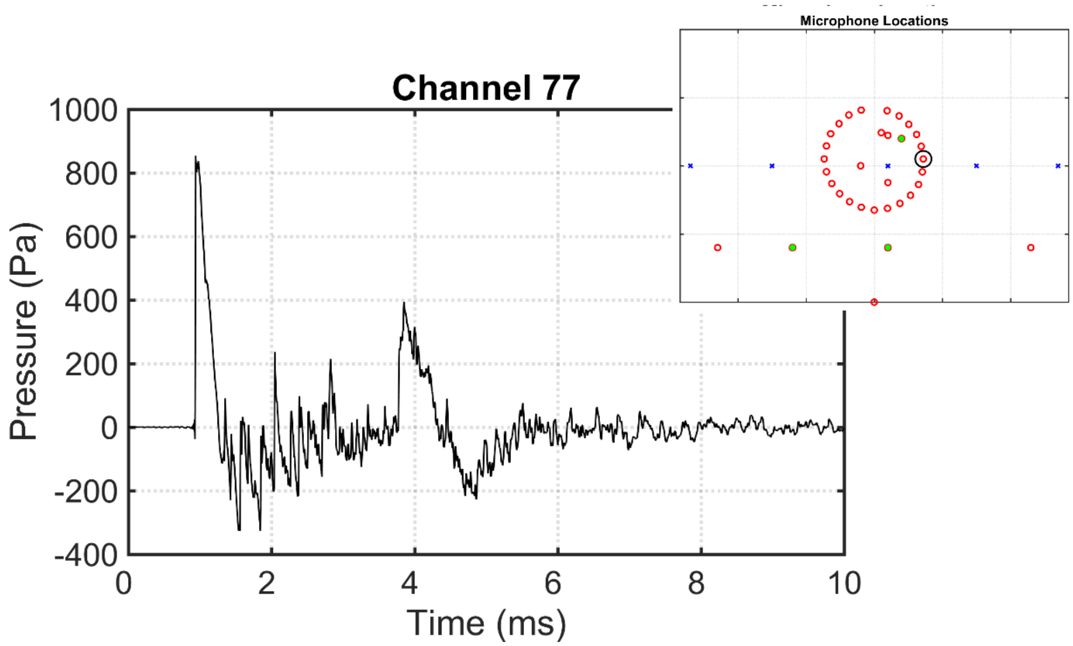

Figure 5. Pressure waveform for another channel in test configuration 11 – Standing right-handed solo shooter standing at the origin. Microphone location shown in top right.

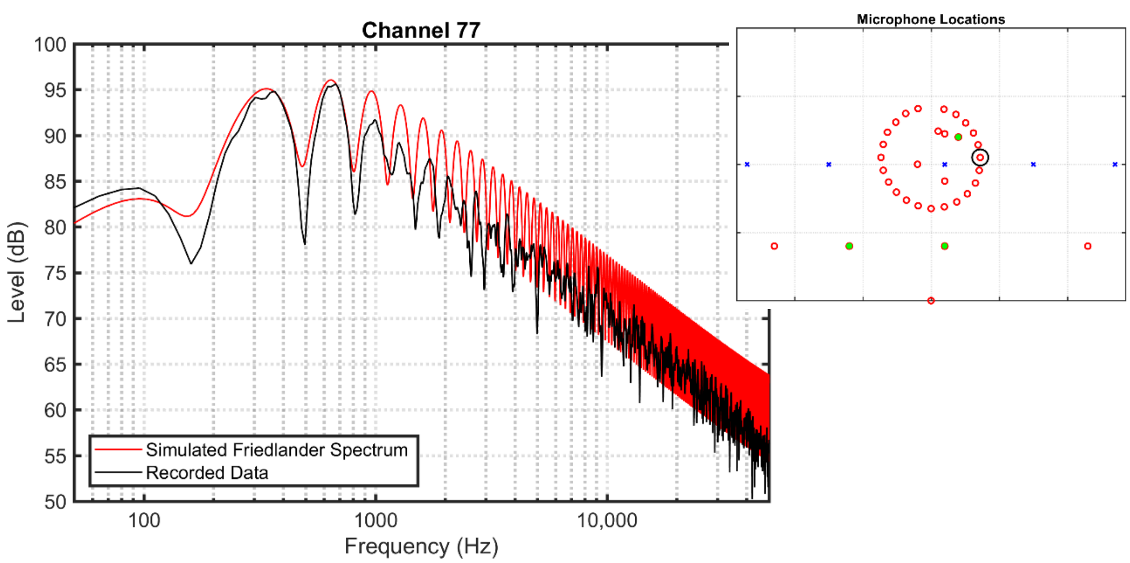

Figure 6. Spectrum for the previous microphone channel. Red line is a simulated high impulse rifle muzzle blast with ground reflection. Microphone location shown in top right.

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Figure *7* shows the pressure waveform for a microphone 10 m directly behind the right-handed shooter standing at the origin. There is significant shielding and scattering by the shooter and weapon, resulting in multiple, relatively lower-amplitude peaks. Figure ***8*** shows the 5 s autospectrum and the spectrum from the simulated Friedlander-plus-ground-reflection spectrum. The peak frequency is in the vicinity as the prior case. The most marked difference in the spectrum is the sharp high-frequency roll-off at 20 kHz, relative to the Friedlander spectrum. This is consistent with increased shock rise time caused by shooter/weapon shielding.

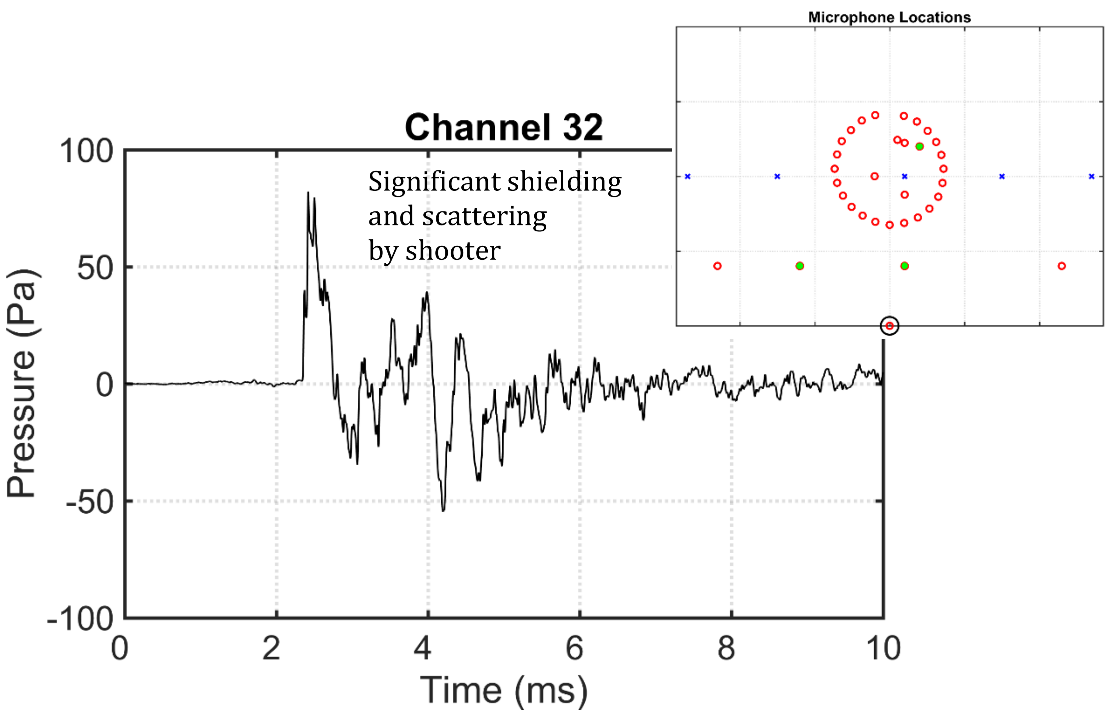

Figure 7. Pressure waveform for another channel in test configuration 11 – Standing right-handed solo shooter at the origin. Microphone location shown at top right.

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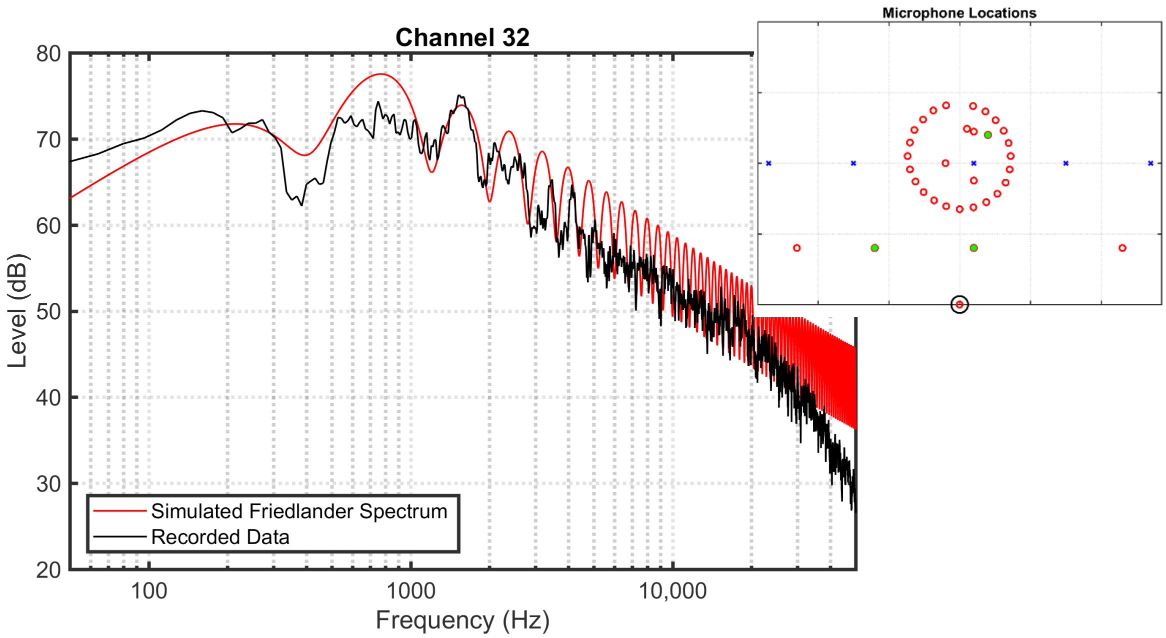

Figure 8. Spectrum for the previous microphone channel. Red line denotes the simulated Friedlander spectrum with a $1/f^2$ falloff. Microphone location shown in top right.

Another waveform analysis that can be performed is to examine the impact of shooter and microphone (i.e., listener ear) height on the waveform characteristics. For point sources and receivers, reciprocity would dictate that interchanging the source and receiver would yield the same waveform for a given shooter/microphone configuration. However, an initial analysis reveals that direct measurement of different shooter positions and microphone heights is important in the MIL standard. Figure ***9*** shows two different figures comparing waveforms for different configurations. The top figure shows the measured waveforms for a standing shooter and microphones at prone, kneeling, and standing heights, whereas the bottom figure compares the waveforms at a standing-height microphone and the shooter changing to prone, kneeling, and standing positions. Thus, the two blue curves (standing shooter/standing microphone) are the same for comparison. While the peak levels may be similar, an examination of the kneeling and prone waveforms show marked differences that may impact noise dosages.

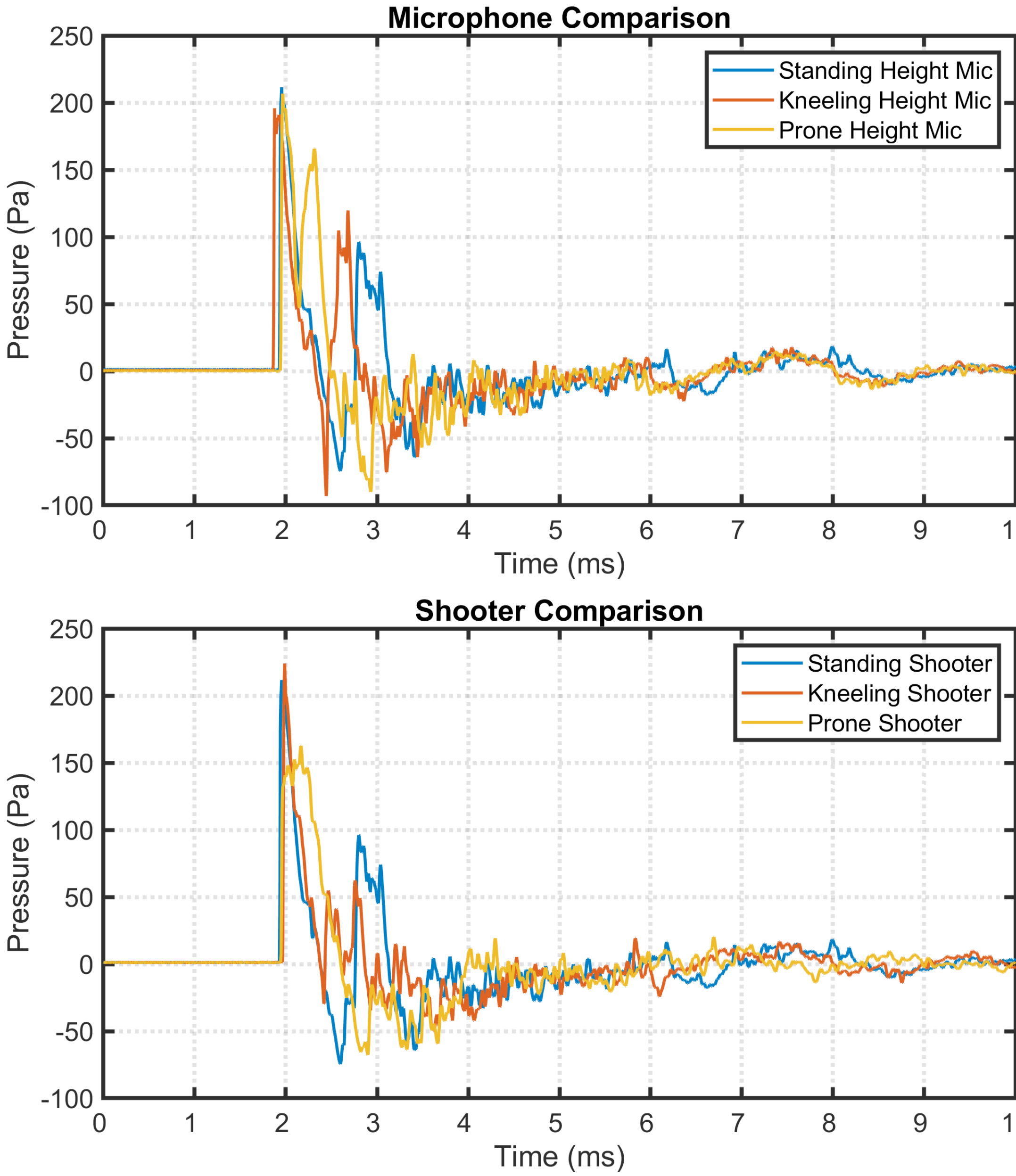

Figure 9. Two figures to compare shooter height and microphone stand height. The top graph shows a standing shooter recorded at three different microphone heights. The bottom graph shows a single microphone at standing height for standing, kneeling, and prone shooter heights.

E. CONSISTENCY

In accordance with MIL-STD-1474E, the consistency between shots of a recording was analyzed. Figure ***11*** shows the 10 ms Equivalent Level (L_{eq10ms}) for an entire recording. The L_{eq10ms} was calculated using a moving average. The red box points to the consistent peaks between each shot, with a spread of less than 3 dB over the 10 shots and a standard deviation of 0.41 dB.

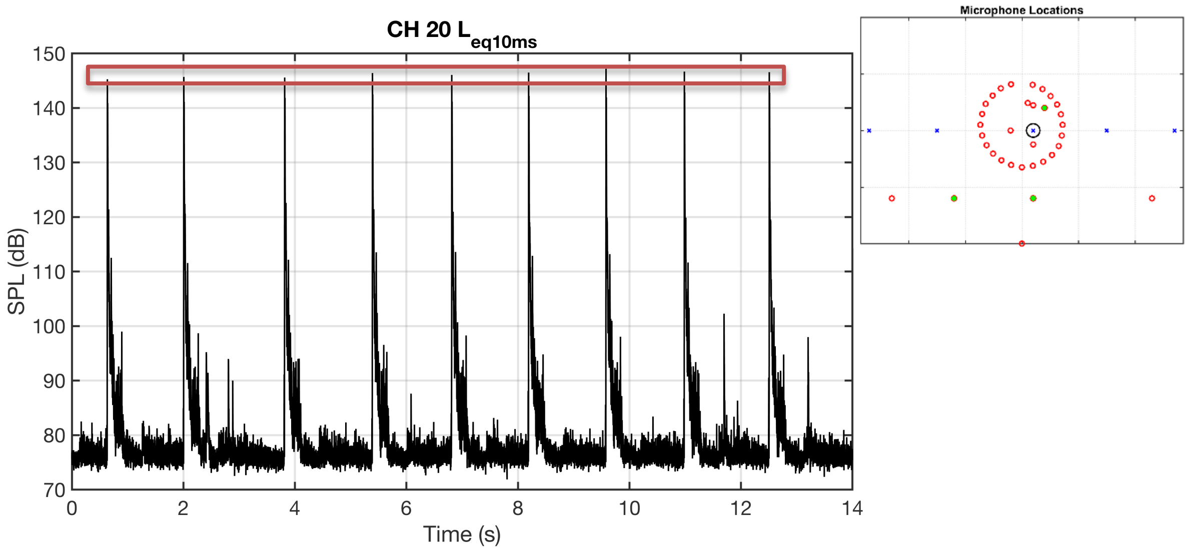

Figure 10. Running 10 ms Leq pressure waveform for channel 20 in test configuration 11 – Standing right-handed solo shooter at the origin. The red box illustrates the consistency between each shot in the recording. Microphone location shown in the top right.

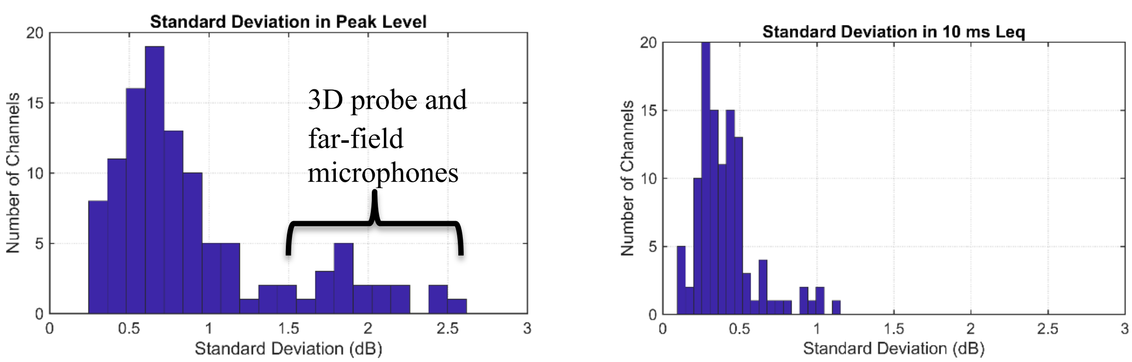

Figure 11. Standard deviation for the peak level and running 10 ms Leq of all 113 channels between all 10 shots in the configuration. Configuration 11 – Standing right-handed solo shooter at the origin.

Whereas Fig. ***10*** shows the consistency for 10 shots at a single channel, Fig. ***11*** shows the standard deviation in L_{pk} for all 113 channels as a histogram. The average of all those standard deviations is 0.92 dB. The microphones with the most deviation are the 3D intensity probes (which, because they house four microphones and have a larger housing, may be more sensitive to scattering) and those along the far-field radials (which are likely caused by atmospheric effects). The same process was repeated and a histogram was created for the 10 ms equivalent level. One can see that the average in standard deviation of 0.41 dB across all channels, which is lower than the L_{pk} standard deviation, with only three microphones having a standard deviation over 1 dB.

F. SPATIAL PLOTS

Examining the data for spatial smoothness and/or reasonableness is also important. Figure ***12.*** shows an example polar plot made with the microphone channels along the arc. This plot shows a comparison between levels for shots fired from a right-handed shooter and the mechanical gun stand. The overall level for the shooter is up to 6 dB lower, denoting potential damping (shielding) from the shooter himself. The most significant shielding is in the rear, what one would expect from a right-handed shooter. Though not shown, the left-handed shooter sees similar shielding at the rear of the arc. The curves are smooth and appear physically consistent.

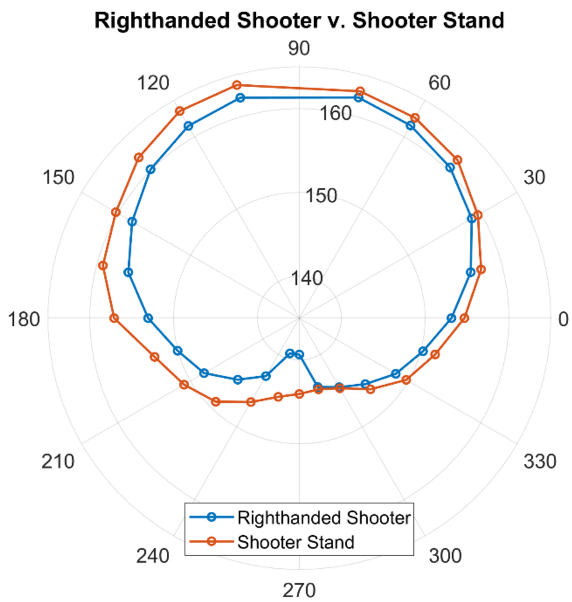

Figure 12. Polar plot of peak level around the polar arc. Shooter at the origin.

The spatial plot in Figure ***13*** shows an interpolated map of the L_{pk} experienced at each channel (represented by the white dots). The black contour line represents a 140 dB threshold. Again, the effects significant shielding are seen to the rear of the shooter. Personnel within this range (roughly 20 m from the central shooter along the firing lineup and as far back as 5 m behind the line) receive peak levels higher than 140 dB and are required to wear hearing protection according to DoDI 6055.12[18]. However, peak level is not the only metric for which a hearing protection criteria is defined; the DoDI also specifies that sufficient hearing protection is required to keep personal noise exposures below an 8-hour time-weighted average (TWA) of 85 dBA (A-weighted). The TWA criteria depends not only on the sound field from a single shot, but additional operationally relevant parameters such as the number of shots fired from each weapon, the number of shooters on a range, and the relative locations of all personnel to the shooter lineup. Total noise exposures will be addressed in future publications, but MIL-STD-1474E specifies that a critical element of this process involves the calculation of short-duration equivalent levels for impulsive weapon systems. Figure ***14*** shows the interpolated spatial map of the average 10-millisecond unweighted equivalent level for a single shot, L_{eq10ms}. The spread is much more symmetrical, as expected, as the equivalent level metric is an indicator of the total sound energy from the shot arriving at the microphone.

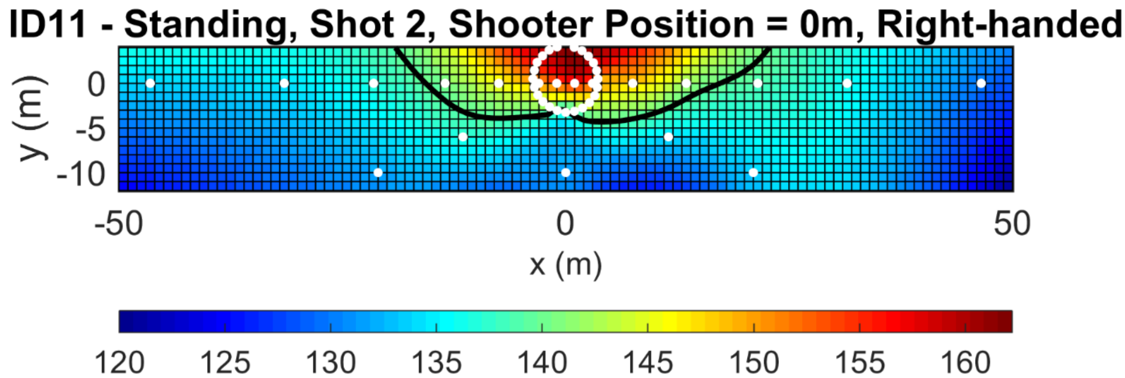

Figure 13. Peak level spatial plot of configuration 11 – Standing right-handed solo shooter at the origin.

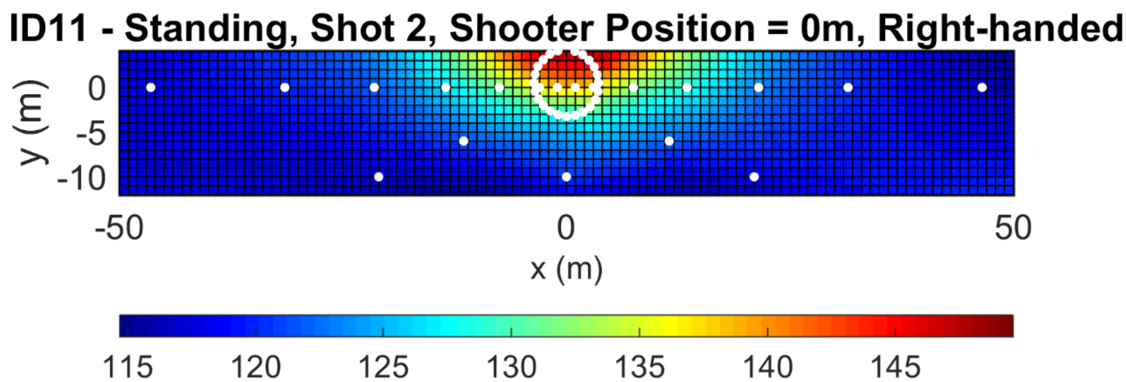

Figure 14. Spatial plot of 10 ms equivalent level of configuration 11 – Standing right-handed solo shooter at the origin.

The spatial decay of sound levels along the firing line also shows physically consistent behavior. Figure ***15*** compares peak sound pressure levels recorded as a function of distance from the shooter, for three shooters at -18 m, 0 m, and 18 m. For each set of points, the data were plotted with the shooter location becoming the new origin. The data are smoothly varying and follow a consistent decay pattern just as Nikolaos showed for small firearms[10]. Due to consistency, one can argue that the use of either roving microphones or a stationary array with a moving marine both to be viable options for future measurements.

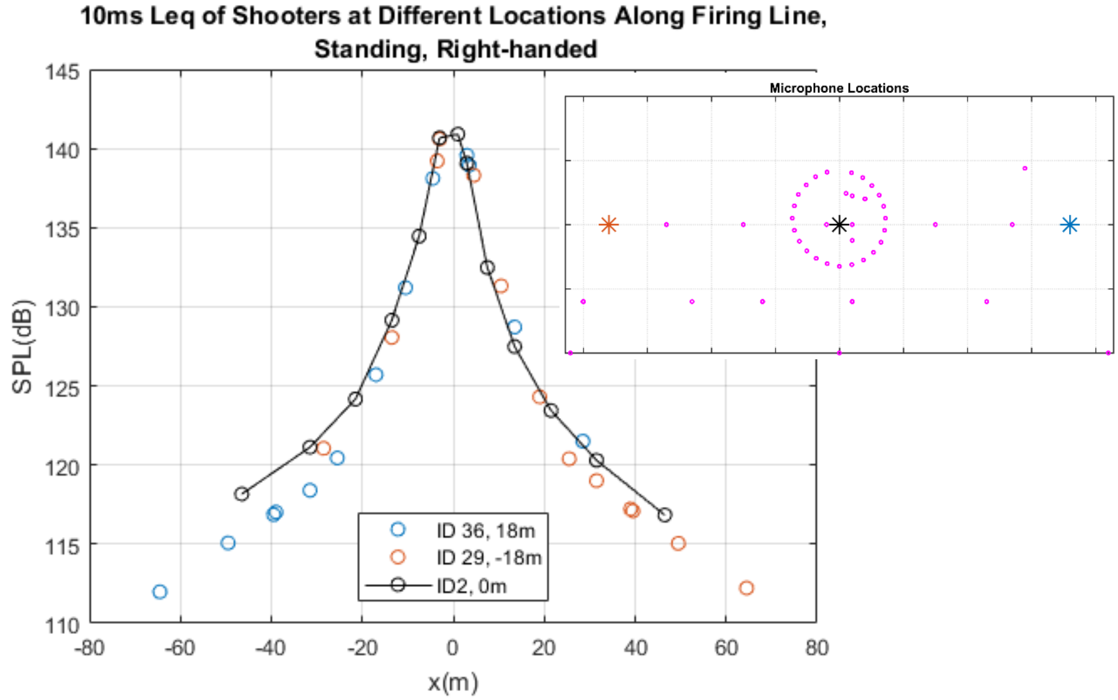

Figure 15. Comparison of standing right-handed shooters at -18 m, 0 m, and 18 m. Locations are shown in the top right. Relative positions are plotted for comparison.

4. CONCLUSION

The analyses thus far show that the data collected are of high fidelity and are useful for developing an improved understanding of weapon noise emissions. Waveform inspection showed that no data clipping or transient saturation effects caused by preamplifier overloading[14] occurred. Further analysis has shown that the peak levels have a small standard deviation, thus showing shot-to-shot consistency and establishing a baseline for future measurements of other weapons. In the future, the data will be used to begin development of a physics-based model for dosage calculations, which will be accompanied by an improved understanding of measurement requirements for model development. Further analyses, such as acoustic imaging of the source using beamforming, will improve understanding of ballistic weaponry noise sources. Additional analyses will be directed at refining measurement recommendations in MIL-STD-1474E.

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