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Cumulative noise exposure model for outdoor shooting ranges

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An impulsive noise exposure model for outdoor military shooting ranges was created. The inputs to the model included spatial interpolation of noise exposure metrics measured from a single round of fire from a small-arms ballistic weapon. Energies from this single-shot model were spatially translated and summed to simulate multiple shooters firing multiple rounds based on the equal energy hypothesis for damage risk assessment. A validation measurement was performed, and the uncertainties associated with measurement and modeling were shown to be acceptably low. This model can predict and assess total exposures and protection measures for shooters, instructors, and other range personnel. https://doi.org/10.1121/1.5132289

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I. INTRODUCTION

Permanent hearing loss among military personnel following basic training with ballistic weapons shooting has been documented to be about 13%.[1] Anecdotal evidence also suggests that hearing loss among military shooting range instructors may be common. Hearing loss could likely be reduced through increased compliance with hearing protection measures that achieve national noise exposure daily limits.[2] However, an assessment of compliance requires knowledge of the noise levels to which instructors and trainees are exposed during shooting range exercises.

A predictive model of 8-h time weighted average levels on shooting ranges is desired, which is the same as the 8-h A-weighted equivalent level (L_{Aeq8hr}) when a 3-dB-per-doubling exchange rate (i.e., the equal energy hypothesis) is used.[2] This paper presents a cumulative noise exposure model for outdoor shooting ranges based on (1) a model of sound field levels during a one-round firing of a weapon, (2) the locations of shooters/instructors relative to each weapon fired in a multi-shooter lineup, and (3) the number of rounds fired from each weapon, similar to the process performed for a Glock 17 pistol in 2012.[3] Special consideration is made for the practical challenges associated with measuring a shooter's noise exposure from their own weapon.

The single-shot model is developed here for the M16A4 military rifle using data collected on an outdoor shooting range at the Weapons Training Battalion (WTB) in Quantico, Virginia, 2017. A validation of the cumulative model is also performed by comparing a simulated multi-shooter sound field to benchmark measurements made during a real life exercise.

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II. EXPERIMENT

The M16A4 measurement at the WTB involved more than 100 microphones and resulted in a dataset that can be studied for high-resolution acoustic source models; propagation effects of weapon directivity,[4] ground reflections, and nonlinearity; and improved measurement techniques for impulse noise exposure studies. A comprehensive description of the experiment can be found in Ref. 4. Sub-arrays of microphones for the model and validation work in this paper are described here. All data were collected in accordance with national[5] and military[6] standards for impulsive sources.

Since noise exposure was a primary objective of the data collection, the Cartesian coordinate system used in this paper is centered on the head location of the primary shooter with $x = 0$ m and $y = 0$ m located approximately between the shooter's two ears, and a height z above the ground. Microphone locations are shown in Fig. 1. First, a microphone grid was deployed along the shooter lineup ($y = 0$ m) and throughout the "instructor area" as far as $y = -10$ m (behind the lineup) at an average ear height $z = 1.56$ m of a standing shooter. Another set of microphones was deployed along arcs centered on the approximate location of the weapon muzzle ($x = 0$ m, $y = 0.5$ m, $z = 1.46$ m). The main arc array had a radius of 3.7 m with microphones placed every 15° and one 30° gap centered in the direction of fire. Last, a specialized subset of microphones was deployed (not shown in Fig. 1) in order to collect data at the head locations of personnel in the lineup *without a person present* (i.e., a "hearing zone"[7] condition) as required by current regulations.[5,6] Two "roving" microphones at head height were moved along $y = 0$ m to various locations at the center of the shooting lanes (3 m spacing between lanes was assumed). Two more microphones were mounted onto a low-profile (minimal acoustic scattering)

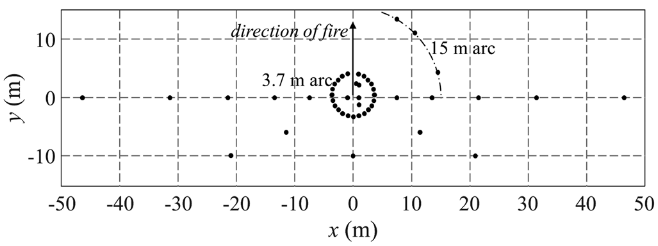

FIG. 1. Shooting range microphone schematic, top view.

custom test stand at the locations of a shooter's left and right ears relative to the weapon, also mounted on the test stand and fired from a distance using a lanyard.

Multiple configurations of weapon firing occurred with the M16A4 rifle in order to capture the most relevant physical acoustics phenomena that affect personnel noise exposures on a shooting range. First, the weapon was fired by a shooter standing alone at the center of the firing line. A total of 20 rounds were fired in slow succession, with 2–3 s between each shot to allow reverberant sound waves to decay. Then, in order to study the scattering and shielding effects that the bodies of multiple shooters have on the sound field in a realistic scenario, the measurement was repeated with an additional 6 personnel occupying the shooting lanes to the left and right of the shooter (12 total) and spaced every 3 m. These personnel held weapons at the ready as if they were firing, but only the central person fired the weapon. The shooter fired 6 repeated sets of 10 rounds each. For each set, two people were removed from the lineup and replaced by the roving microphone in their hearing zone. Finally, a multishooter exercise took place with the 12 personnel to the left and right firing 10 rounds each at will, and the person in the center lane replaced with the weapon mounted on a stand and fired from a distance by a tether. For all firing scenarios, the weapon was pointed in the direction of increasing y with the muzzles at approximately $y = 0.5$ m.

III. CUMULATIVE EXPOSURE ESTIMATION METHOD

The various data collection points were combined to create a cumulative noise exposure model based on A-weighted equivalent levels using the equal-energy hypothesis for damage risk assessment. Some evidence suggests that A-weighted equal-energy metrics may not be the optimal criteria for true impulse damage risk assessment,[8,9] but L_{Aeq8hr} did outperform other metrics for the prediction of blast overpressure injury data in a 2009 study.[10] The cumulative model was implemented here using L_{Aeq8hr} as the basis for hearing damage specified in criteria current national regulations,[2,6] but this approach could be used with any metric that uses an equal-energy model.

The measurement and modeling process is outlined in Fig. 2, down the left side. First, the impulsive A-weighed equivalent 100 ms level, $L_{\mathrm{IAeq100ms}}$,[6] was calculated for select microphones (locations shown by dots in Fig. 3) with a single shooter and adjacent lanes occupied by personnel. $L_{\mathrm{IAeq100ms}}$ is to the standard L_{Aeq8hr} damage risk metric through the multiplicative constant $100\,\mathrm{ms}/8\,\mathrm{h} = 0.000\,003\,47$ applied energetically, or alternatively, $L_{\mathrm{Aeq8hr}} = L_{\mathrm{IAeq100ms}} - 54.6$ dBA.

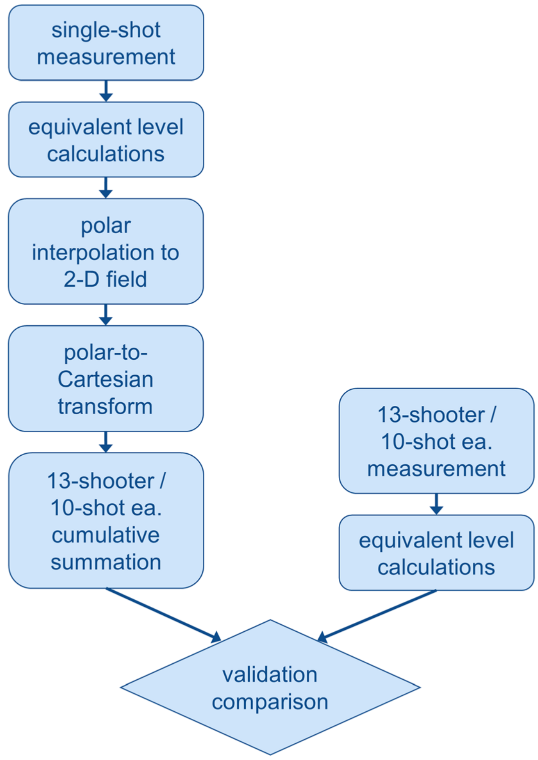

FIG. 2. (Color online) Data flow chart. Left track: measurement and cumulative modeling process. Right track: validation measurement process.

Next, these data were interpolated over a grid covering the firing line and instructor area by transforming the microphone locations to a polar coordinate system centered on the muzzle location, performing a thin-plate spline interpolation in polar coordinates, then evaluating the interpolation at the Cartesian grid points transformed to the same polar coordinates. This interpolation method was chosen over other spline or polynomial algorithms because it minimized nonphysical artifacts in the regions where sampling density was lowest. The result of this interpolation for a single shot is shown by the contour map in Fig. 3. A color bar is included in Fig. 3 to show values in both $L_{\mathrm{IAeq100ms}}$ and L_{Aeq8hr}. The weapon directivity is apparent in this field map with the main sound energy being focused in the forward direction. Note that the top 10 dB of energy is all located within about 5 m of the shooter. The interpolation algorithm leads to some non-physical features in areas where the field sampling was sparse (e.g., the localized maxima near $x = -35$ and $+35$ m), and the asymmetry of the forward array may contribute to some of the field asymmetry. However, higher spatial sampling in the regions that contribute most to cumulative exposures allowed for robust interpolations. Uncertainties due to the interpolation will be included in the error analysis below, and higher precision weapon asymmetry analyses are included in Ref. 4.

The final step in the cumulative model was to translate the single-shot sound field grid centered on $x = 0$ m to multiple locations centered on all shooting lanes. These superposed fields were summed energetically, and the energies were multiplied by the number of rounds fired by each shooter in a simulated exercise. The critical assumption in this process is that

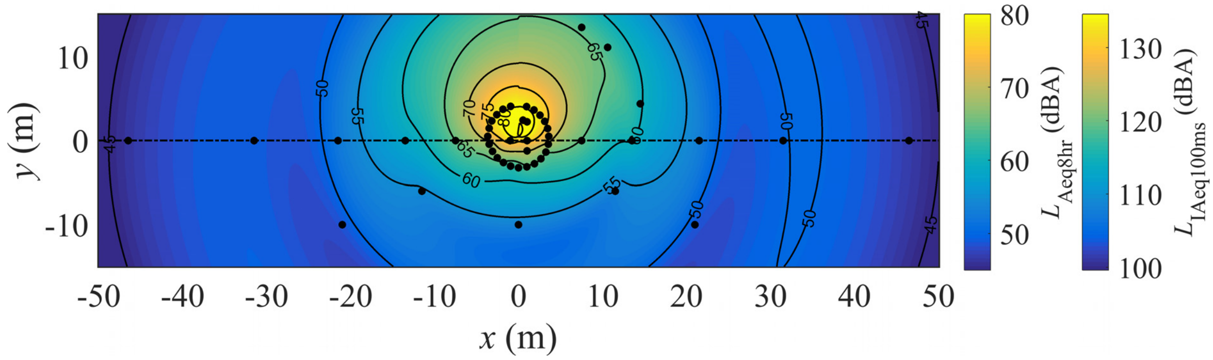

FIG. 3. (Color online) Interpolated L_{Aeq8hr} values at head height for a single shot using the measured inputs marked by circles. Values converted to $L_{\mathrm{IAeq100ms}}$ are indicated by the rightmost color bar.

the impulse waves arriving at a listener from different angles produce comparable (angle-independent) exposures. Although head shielding and other phenomena can create significant left-ear/right-ear exposure asymmetries for a single shot, the cumulative model compensates by incorporating multiple noise sources distributed on both sides and in front of each listener, essentially averaging out these asymmetries. A detailed analysis of the validity of this assumption and the potential benefit of angle-of-incidence exposure corrections are anticipated in a future study.

IV. ERROR ANALYSIS AND OPERATIONAL SIGNIFICANCE

The objective of this section is to discuss the uncertainties associated with potential errors and variability in the measurement and modeling process. Note that a 3-dB-per-doubling exchange rate in the damage risk criteria translates into a halving (50% impact) of the number of daily allowed operations, such as the number of rounds fired by a shooter. For the purposes of this work, a 2 dB difference (37% impact) is considered an operationally significant threshold. Level uncertainties or differences less than 2 dB might be considered negligible. Another argument in favor of a difference threshold near 2 dB is the fact that variations in the actual performance of hearing protection devices and in individual susceptibility of humans to noise exposure are much higher than the measurement uncertainties.

Measurements made away from the central shooter had standard deviations less than 1 dB, but uncertainties were 2–3 dB within about 5 m of the shooter due to small variations of weapon position and the difference between a measurement made directly in a hearing zone and an interpolation across two microphones on either side. Differences in occupied and unoccupied range levels were under 2 dB at all locations, so the effects of acoustic scattering from personnel is considered negligible.

The total uncertainty of a noise exposure prediction on a shooting range is due to a combination of the factors discussed above as well as low-order effects like microphone calibration, left/right asymmetry of the M16A4 weapon directivity,[4] different body shielding effects behind a left-handed vs right-handed shooter, and shooter body height. Taken together, the total uncertainty of the predictive noise exposure model is 3–4 dB. Since the uncertainty ascribed to a single shot could be considered a percentage of the exposure energy, and since total exposure dosage is based on energy summation, the uncertainty of 3–4 dB is applicable to single shots or cumulative summations of multiple shots. In other words, the total dosage uncertainty is not dependent on the number of shots.

V. RESULTS AND VALIDATION

An example of a cumulative shooting range noise exposure scenario using the modeling method described above is shown in Fig. 4. This model represents 13 shooters in adjacent

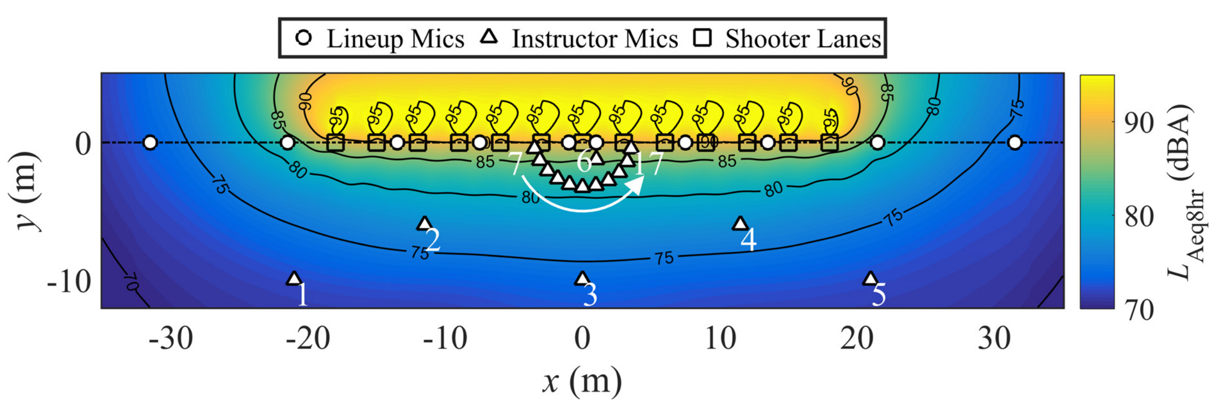

FIG. 4. (Color online) Cumulative sound exposure map for a 13-shooter (10 rounds each) scenario.

lanes spaced 3 m apart along a lineup (marked by squares), firing 10 rounds each. The contour map shows the L_{Aeq8hr} values over the entire shooting range. One critical feature of this sound field is the fact that the cumulative exposures for the personnel at the ends of the lineup ($x = +18$ and -18 m) are only about 1 dB less than the exposures of those toward the center. This is because the majority of the noise exposure comes from each shooter's own weapon, which produces levels 5–6 dB higher than the levels from the nearest-neighbor weapons.

The model shown in Fig. 4 was chosen because it was identical to a 13-shooter (10 rounds each) exercise measured at the WTB, the data from which can be used for model validation. The circles and triangles in Fig. 4 show the locations of microphones along the shooter lineup and in the instructor area, respectively, relative to the shooting lanes during the measurement. Figure 5(a) shows the modeled cumulative exposures along the lineup (solid line), benchmark measurements along the lineup (circles), and the benchmark mean level measured at the two shooter hearing-zone microphones fixed to the weapon stand (dashed line). The 1-dB oscillations in the cumulative model between $x = -20$ and $+20$ m reflect the weapon directivity, with local minima at the lane centers (directly behind the weapons) and local maxima in between. The measured level in the hearing zone is 1 dB higher than the hearing zone levels at the lane centers but falls well within the 3–4 dB near-field uncertainty. All model and benchmark comparisons, both inside the lineup and out to $x = \pm 47$ m from the center, are within 2 dB.

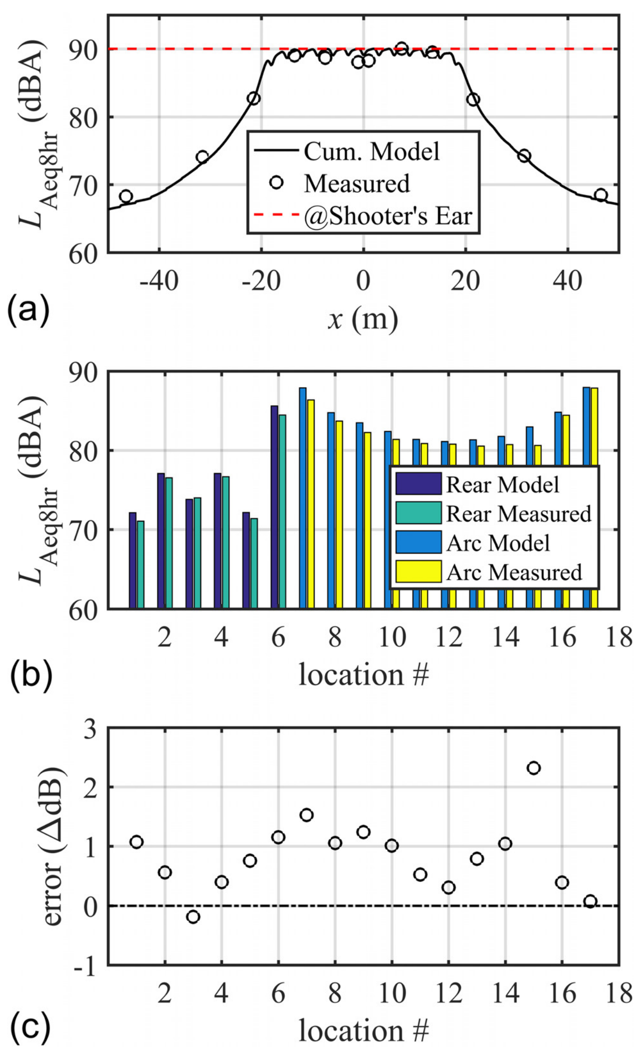

FIG. 5. (Color online) (a) Comparison of cumulative model and benchmark measurements for the 13-shooter exercise at the shooter lineup. (b) Comparison of cumulative model and benchmark measurements at 17 locations in the instructor area (see Fig. 4). (c) The dB differences between the modeled and measured values in the instructor area.

Modeled and measured cumulative levels in the instructor area are compared in Fig. 5(b). These data are taken from distinct locations in the space behind the shooter lineup (locations #1–#6 in Fig. 4) and along the rear portion of the 3.7 m arc (locations #7–#17 in Fig. 4). The differences between modeled and measured cumulative levels are shown for the same instructor locations in Fig. 5(c). All the exposure level comparisons differ by less than 2 dB, including at locations #1–#5 where spatial sampling densities for the model creation were low. The one exception is location #15, where the measured levels are anomalously low (2.4 dB less than the model). Further investigation is needed to determine if this is due to measurement error or due to a physical phenomenon, such as shielding effects during the 13-shooter exercise.

VI. DISCUSSION AND CONCLUSION

A cumulative noise exposure model was created for outdoor shooting ranges, where data collected for single-round firings of an M16A4 were used to simulate multiple shooters firing multiple rounds. Noise exposures were modeled for personnel in the shooting lineup and in the instructor area behind the lineup. Comparisons to physical measurements at these locations during a multiple shooter exercise showed that the model was accurate for this scenario within 2 dB or less at most locations, with the caveat that uncertainties could exceed 3 dB in the geometric near-field where noise exposures are highest. For the purposes of noise-exposure estimation using this modeling approach, the effects of an occupied vs empty shooting range lineup, interpolation instead of direct measurement at personnel hearing zones,[7] and other sources of measurement uncertainty were found to be negligible. These effects could be non-negligible for higher-order acoustic analyses, such as precise determination of peak levels or nonlinear propagation, but the measurement and modeling techniques presented here are deemed adequate and practical for a cumulative exposure model.

The assessment of real-life exposures will of course require the application of hearing protection to the model presented here. Impulsive-peak-insertion-loss[11] attenuation levels can be applied directly to the L_{Aeq8hr} values calculated at personnel hearing zones to estimate their protected exposures.

One of the most important findings from this analysis is that the noise exposure from the M16A4 is dominated by the impulsive wave from the shooter's own weapon, with combined exposures from all other weapons in the lineup adding only 3–4 dB to the total exposure (with 3-m spacing between shooters). Therefore, protective measures such as noise suppression and hearing protection will benefit most by reducing noise levels in the near field and behind the weapon.

Future work for shooting range exposure assessment is focused on the simplification and standardization of impulsive weapons measurement and modeling techniques. In addition, many acoustic datasets have been collected on a variety of military and recreational weapons[12] that might be modeled in a similar manner and included in a noise exposure model. Other research efforts that could enhance the capabilities of shooting range exposure models are the inclusion of surface reflections for covered and indoor ranges; altered models for weapons fired from kneeling, sitting, and prone positions; and the replacement of the spatial interpolation model used here with physics models for the muzzle blast wave and the ballistic shock wave from supersonic bullets. Such physical models combined with an expanded weapons database could ultimately lead to a high-fidelity noise prediction model based on weapons parameters like barrel length, bullet caliber, and exit velocity, which could eliminate the need to collect data on every weapon.

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