ARL-TR-9277 • AUG 2021

Quantitative Human Factors for Small Arms Suppression Field Effects

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David F Dye

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ARL-TR-9277 ● AUG 2021

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED (From - To)
August 2021	Technical Report	1 June 2019–1 June 2021

4. TITLE AND SUBTITLE Quantitative Human Factors for Small Arms Suppression Field Effects	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Paul D Fedele, Mark A Ericson, Kim F Fluitt, Gregory S Oberlin, Daniel L Cler, Adam M Jacob, and David F Dye	**5d. PROJECT NUMBER** WR 0042540.53.1
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) DEVCOM Army Research Laboratory ATTN: FCDD-RLH-FC Aberdeen Proving Ground, MD 20005	**8. PERFORMING ORGANIZATION REPORT NUMBER** ARL-TR-9277
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) DOD Joint Services Office, Small Arms Program The Pentagon 1400 Defense Blvd, Washington, DC 20301-1400	**10. SPONSOR/MONITOR'S ACRONYM(S)**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release: distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The Department of Defense Joint Services are pursuing the application of suppressors on small arms. Small arms suppression will reduce Soldier risk of auditory damage from impulsive muzzle blast exposure, improve Soldier ability to understand speech, and help Soldiers maintain auditory awareness of their surrounding environment. In addition, small arms suppression and signature reduction will make it more difficult for the enemy to detect and localize Soldier firing positions. Suppressors can also improve Soldier marksmanship by reducing the intensity of muzzle blast impulses, capable of pre-triggering the startle reflex. This report describes methods for quantifying the effects of small arms signature suppression on human performance processes. Where available, existing perception models are applied to evaluate the expected field effectiveness of suppressors. Where previous modeling work is nonexistent, we apply related research results to create new models to estimate the expected impact of suppressor use on human performance in the field. As field performance data become available, the new models can be updated and validated when possible. The methods and models described here allow quantification of the facilitative effects of suppressors on performance and can support suppressor acquisition.

15. SUBJECT TERMS

suppressor, small arms, perception, audition, visibility, stealth

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Paul D Fedele
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (Include area code)
Unclassified	Unclassified	Unclassified	UU	59	(410) 278-5984

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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1. Introduction/Background

The Department of Defense Joint Services are seeking to develop suppressors for small arms and have formed a Suppressor Integrated Process Team (IPT) to research aspects of suppressor function, design, and manufacture. IPT efforts are currently measuring and modeling suppressor influences on small arms signatures. Suppressing both muzzle flash and muzzle blast are primary program objectives. Thus, both muzzle flash and muzzle blast are being measured. Physical models are being developed to help predict muzzle blast and flash reduction based on ammunition and weapon characteristics and physical suppressor geometries and material properties (Oberlin and Cler in prep). From the physical performance of suppressors, we attempt to quantify how small arms signature suppression in the field will impact the Soldiers and civilians using suppressed small arms and how suppressed small arms influence the human perception of small arms fire. In this report, we consider how suppressed small arms signatures influence Soldier performance and how they may inhibit the performance of enemy combatants.

We quantify suppressor influences in Soldier stealth, auditory communication capability, auditory environmental awareness, hearing damage risk from muzzle blast, and possible influences of muzzle blast suppression and blowback on marksmanship.

1.1 Soldier Stealth

The influence of suppressors on Soldier stealth considers how the enemy perceives small arms signatures. Suppressors have been used with small arms for over 100 years; a historical summary of suppressors is available by Truby (1972). Although suppressors have been called *silencers*, they do not make small arms silent. While suppressors can reduce the level of a muzzle blast, suppressed small arms signatures still consist of audible sounds. Small arms signatures also may consist of a visible flash. Soldier stealth is improved when the enemy cannot detect small arms fire from the Soldier. As the first consideration for Soldier stealth, we examine the (human) auditory and visual detectability of suppressed small arms signatures. We consider the human ability to detect auditory and visual components of small arms signatures at likely positions of enemy personnel. Soldier stealth improves as the maximum detectible ranges of auditory and visual stimuli detection decrease.

Stealth is also improved when the enemy cannot accurately determine the direction to the shooter's location from the enemy's position. We refer to determining the direction of the shooter as the process of localization. We consider localization in the azimuthal angle in the horizontal plane. When the enemy cannot localize the shooter, accurate direct return fire is not possible. To quantify small arms suppressor effects on Soldier stealth, we model the expected perceived origin of small arms stimuli. Determining the distance to the shooter allows the establishment of accurate return fire. Currently, we do not consider the influence of small arms suppressors on the enemy's ability to determine the distance to the shooter. Here, we are addressing direct return fire only.

1.2 Auditory Communication

The muzzle blast of small arms reduces the ability of Soldiers to communicate. Auditory communication primarily consists of speech. Weapons fire can reduce comprehension of speech and suppressors may reduce that impact. We extend existing measures of speech intelligibility in an effort to describe this effect.

Auditory communication capability in the presence of noise was quantified using the articulation index (Fletcher 1921). The articulation index evaluates speech communication capability by summing the weighted differences between the frequency-dependent amplitude of the speech and the frequency-dependent amplitude of the noise. The frequencies are weighted by their importance in speech communication. Fletcher's (1921) articulation index is designed to apply to telephone systems; the applied amplitude ranges were selected based on comfortable speaking levels, so telephone systems could be evaluated based on user comfort. Many references describe quantified speech communication capability, using the articulation index or similar metrics (French and Steinberg 1947; Kryter 1962; Pavlovic et al. 1986; Mueller and Killion 1990; Payton and Braida 1999). A number of speech intelligibility metrics are described and discussed by Letowski and Scharine (2017).

To model speech communication for Soldiers involved in fire fights, we begin with the articulation index, as described in the Siemens Digital Industries Software Community Article titled *Articulation Index* (Mila 2019), and we modify the amplitudes used in the calculation to include loud shouting (i.e., higher amplitudes than those considered practical or desirable in telephone systems). We apply this modified articulation index with noise representing suppressed and unsuppressed small arms fire to quantify how suppressors may improve Soldier ability to receive auditory speech communication.

1.3 Environmental Auditory Awareness

Speech communication is not the only benefit Soldiers get from audition. Soldiers indicate they often choose not to use passive hearing protection when enemy contact is possible because the protection impairs their ability to hear sounds in their environment. The human auditory channel evolved to indicate the presence or lack of danger and advantage in our immediate environment. While speech communication metrics are adjusted for the information content of speech in each frequency band, no similar data is available for specification of the greater or lesser relative importance of different frequency bands for determining environmental dangers, or lacks thereof, in the surrounding environment. We hypothesize the ability to hear these environmental sounds is required to establish and maintain auditory environmental awareness. We hypothesize that Soldiers hesitate to use passive hearing protection when enemy contact is possible because the passive hearing protectors reduce the auditory channel capacity for information transfer from the surrounding environment. On this basis, we evaluate the Soldier's ability to maintain auditory environmental awareness by the channel capacity of the entire auditory system without regard to the relative information content of each frequency component or component amplitudes. Like the speech communication channel capacity, the environmental auditory channel capacity is evaluated from the level of the hearing threshold plus the environmental noise to the upper level of hearing capability. The upper level is taken from the Siemens Digital Industries Software Community Article (Mila 2019).

1.4 Hearing Damage Risk due to Muzzle Blast

Impulsive muzzle blast exposures are hazardous to hearing. A hearing loss in frequencies near 4 KHz has been associated with shooting firearms since before 1860 (Toynbee 1860; Clark 2002). Shooter's notch occurs in people who do not wear hearing protection and shoot firearms even casually, as in hunting (Peck 2001). The varied characteristics of impulse noise make it difficult to assess auditory damage based on any single noise characteristic. The US Army Combat Capabilities Command Army Research Laboratory, Human Research and Engineering Directorate (HRED) created the Auditory Hazard Assessment Algorithm for Humans (AHAAH) to evaluate auditory damage risks from exposure to varied impulse sounds. AHAAH assesses hearing damage by simulating the human auditory system's dynamic response to the specific details of the waveform and determining the strain-induced breakage of hair cells in the cochlea. AHAAH is the method specified for Army assessment of impulse noise hazards produced by military materiel in the MIL-STD-1474E Military Noise Standard (DOD 2015). The benefit of suppressors in reducing impulsive auditory hazards is demonstrated by comparing the predicted hazard computed using the AHAAH method for impulsive sounds recorded at the shooter's ear location and locations around the muzzle.

1.5 Marksmanship Influences of Suppressors

To achieve good marksmanship, a shooter must generally hold a firearm steady while the shot is fired. We use flinching to describe shooter action when the firearm is not held steady when a shot is fired. Flinching is a response caused by the startle reflex. The acoustic reflex (Møller 1962) is also associated with the startle reflex. The startle reflex can be initiated by many stimuli. Further, the startle reflex can also be initiated in anticipation of startling stimulus, when a precursor stimulus occurs shortly before the primary startle-reflex-inducing stimulus (Brasher et al. 1969). Anticipatory activation may occur only after repeated exposure to the paired stimuli when it is learned that a certain stimulus precedes a startle-inducing stimulus by a short interval. This situation is normally established for military personnel during small arms training. Significant decreases in marksmanship can occur when flinching occurs in anticipation of the shot and both the recoil and the muzzle blast. While suppression may not alter recoil, it will reduce muzzle blast, and as a result, it may reduce startle reflex activation and improve marksmanship. We have developed a model describing the possible reduction in startle reflex activation associated with suppressors. A future goal is to validate this model with marksmanship data gathered as Soldiers continue to fire weapons with and without suppressors.

1.6 Blowback Hazards

Ejection of fired ammunition cases can cause chamber gasses and materials to be blown back toward the shooter. These gasses and materials can present a hazard to the shooter. Because suppressors can delay the discharge of propellant products from the weapon, suppressors can increase the shooter's exposure to propellant products. Test methods used to capture and measure the amount of materials blown from the chamber are being developed and will be used to assess the potential for shooter exposure. The US Army Public Health Command is addressing the hazard presented by these materials for suppressed and unsuppressed weapons. Therefore, we do not address this here.

2. Human Factors of Suppressors

2.1 Stealth: Vision

2.1.1 Visual Detection

Visual detection of the shooter location eliminates all aspects of shooter stealth. While the shooter and the weapon may be well camouflaged and hidden, a visible muzzle flash will give the enemy a precise direction for direct return fire.

Visual acuity will affect visibility. Acuity influences in visibility are directly determined in terms of Snellen visual acuity, which specifies the distance at which individuals can resolve specific line thicknesses, compared to an average person's visual resolution (Holladay 1997). We can correct visual detection ranges by increasing the range for people with better-than-normal vision and decreasing the range for people with poorer-than-normal vision. For example, the detection range for a person with 20/10 vision will be twice that of a person with normal 20/20 vision, and the detection range for a person with 20/40 vision will be one-half that for a person with normal vision. We address visibility to the person with average visual acuity.

Visual detection of light sources has been studied extensively for over a century. Visual stimuli, human visual system adaptation, and the conditions that determine threshold visibility involve many variables. As a result, even though visibility has been long studied, uncertainties remain.

Visual stimuli have been studied by considering the total photopic energy content of a brief flash and from the perspective of the time-envelope of the photopic energy in a general flash. From the perspective of total photopic energy content, the earliest measurements of the lowest amount of light visible to the human eye are attributed to Aubert (1864) by Kalloniatis and Luu's measurements (2014). The physical units used to specify measurement, measurement techniques, and measurement equipment have improved over time.

Today, absolute visibility is evaluated in units of lux.seconds, which gives the amount of photopic energy in lumen.seconds per square meter. Since one lumen per square meter equals 1 lux, the total energy per unit area needed to achieve threshold visibility is given in lux.seconds, or millilux.seconds.

Threshold flash visibility under full dark adaptation was measured by Hecht et al. (1942). These measurements show the smallest amount of light energy that the human eye can see under full dark adaptation. Hecht et al. reported that visual detection requires a minimum energy at the cornea of 2.1 to 5.7 E-10 ergs for light with a reported wavelength of 510 nm (blue-green light). With an approximate wavelength of 500 nm and a 2-mm pupil size, these values correspond to 4.5E-6 and 12.3E-6 mlux.s, respectively. Hecht et al. considered reflection and absorption through the tissues of the eye and examined the statistics of photon dynamics to show that as little as a single photon absorbed in the appropriate retinal structure can produce a cognitive visual perception. Thus, although probability and statistics lead to a broad range for threshold specification, at the lowest limit, a person can experience a visual sensation if just one photon influences the proper receptor in the human eye.

Hennage (2012) measured simulated small arms muzzle flash visibility using blank rounds and 300 observers located at various distances from the muzzle flash. These measurements were obtained at night in an indoor firing range. Hennage used blank ammunition loaded with various charges to produce a wide range of flash energies. Regardless of the specific loading in each blank round, Hennage measured the photopic flash energy (mlux.s) of each shot because the flashes produced by the blank ammunition widely varied. The magnitude of the test and the light conditions were not as controlled as the test process applied by Hecht et al. Because the flashes were produced at the same location and were all accompanied by a muzzle blast, test subjects had a significant indication of where and when flashes were presented. Knowing the flash location and hearing a muzzle blast can increase the tendency to believe a flash was seen. Hennage did not publish his results, but analyses of his results indicate threshold visible flash energies lower than Hecht et al. Hennage's results indicate threshold (50%) visibility is achieved at 9 E-7 mlux.s. Near 100% visibility of the flashes was achieved at 2.3 E-6 mlux.s. Since Hennage's results indicate visibility of less photopic energy than observed in the controlled tests by Hecht et al., the tendency to believe a flash was seen may have been biased by using countdowns preceding each shot and by the presence of the auditory muzzle blasts.

Total photopic flash energy is not the only factor that influences flash visibility. The temporal envelope of the flash also influences visibility. Early work on the visibility of short flashes (Allard 1876) demonstrated a behavior later described as Bloch's Law (Bloch 1885), indicating that visibility was achieved when the product of intensity and duration reached a critical threshold value. Much following work addressed flash visibility from the perspective of time-integration of the intensity of the detected source. This is the limit considered in Hecht et al.'s and Hennage's work.

Because the temporal envelope of a flash can have many varied forms, various schemes for intensity integration were considered by many subsequent authors (Blondel and Rey 1912; Douglas 1957; Schmidt Clausen 1957; Roufs 1971; Ohno and Couzin 2002; Gibbons 2008).

An applied approach to address flicker and repeated flashes is to determine the equivalent steady source as visible and the time-dependent, flickering, or flashing source. Roufs (1971) examined flash and flicker visibility and reported differences between the flash visibility threshold and constant light visibility threshold. Practical investigations of the visibility of vehicle-mounted emergency flashers were performed by Gibbons (2008). Gibbons compared methods of calculating effective visibility intensity, including the Allard method (Allard 1876), Form Factor method (Schmidt Clausen 1957), modified Allard method (Ohno and Couzin 2002), and Blondel–Rey–Douglas method (Douglas 1957). Gibbons demonstrates that the visibility of flashes with differing time dependencies can be accurately, or inaccurately, determined, depending on how the flash characteristics fit those assumed in the creation of the visibility assessment rule.

This condition is analogous to the various impulse characteristics applied to assess auditory damage from impulsive sounds—peak pressure, positive phase duration, amplitude fluctuation decay time—all apply well to waveforms fitting a specific form, but none apply well to all time-dependent waveforms. Gibbons points out that general flash visibility depends on contrast, background luminance, detection probability summation, neurological summation, time integration, and spatial integration; visibility of a general stimulus is not described precisely by any of the time-integrated intensity values alone.

Prior to the work of Gibbons (2008), many of researchers cited previously considered flash visibility from a physiological perspective, including contrast, background luminance, detection probability summation, neurological summation, time integration, and spatial integration. To generalize visibility assessment, Watson (1986) described the human visual response in terms of leaky integrators, using perception analogies based on electrical circuit filter behaviors and analyses.

Watson (1986) examined visibility using physiologically based processes using signal filter principles, applying Fourier analysis to spatial and temporal luminance distributions. This work follows considerable efforts addressing temporal summation, spatial summation, probability summation, and neurological summation. Watson's working model is important in establishing visibility for wide ranges of spatial and temporal luminance and contrast variations.

Watson's working model of visibility shows the limits of applicability of time-integration approaches and illustrates the role of contrast in visibility. Watson's description of visibility processes explains the transition from time-integration processes to time-independent visibility luminance distributions and spatially distributed luminance. Watson's description places visibility on a solid analytical foundation with regard to temporal and spatial luminance distributions and is consistent with the conclusion reached by Bullough and Skinner (2013). Bullough et al. (1991) examined various applied visibility expressions in experimental trials and concluded the approach of Blondel and Rey, as suggested by Douglas (1957), was most applicable to brief flashes like those produced by muzzle blasts.

Watson continues to state:

> There seems little doubt that whatever the other dimensions of the stimulus and whatever the background conditions, there exists a critical duration below which Bloch's law is upheld.

Watson goes on to say:

> If the fitting is confined to durations less than 20 msec, then there are no published instances of a significant violation of Bloch's law.

Watson's comments point out that Bloch's law applies to pulses with durations down to 0.4 μs and as long as 20 ms. It is noted that the duration of small arms flashes are typically less than 1 ms for primary flashes and less than 10 ms for secondary flashes (Dye 2020).

For determining the visibility of small arms muzzle flash, we apply energy per unit area, or illuminance, at the surface of the cornea. When flash illuminance at the location of the observer is equal to the threshold, the person has a 50% probability of seeing the flash. We label the total time-integrated illuminance, or luminous exposure, required for 50% probable visual detection as $E_{.T.}$ with units of lux.seconds, or millilux.s.

A final note regarding color: research shows at threshold detection levels, "…color seems to contribute little to perception of […] high frequency flicker, and spatial integration (Cavanagh et al. 1984; Livingstone and Hubel 1987; Lindsey and Teller 1990)". (Gur and Akri 1992).

Applying the low-end result from the research Hecht et al., the threshold visible luminous exposure at the cornea, $E_{.T.}$, is estimated to be 4.5 E-6 mlux.s, under full dark adaptation.

This measured visibility threshold, $E_{.T.}$, is combined with geometric spreading to provide the maximum range that we anticipate a person with average visual acuity will have a 50% probability of seeing the flash. A muzzle flash producing a total illuminous exposure of E_{flash} at a distance $R_{measurement}$ will produce 50% probable visibility at a range $R_{.T.}$, where $R_{.T.}$ is given by

$$R_T = \sqrt{\frac{E_{flash}}{E_T}}\, R_{measurement} \tag{1}$$

An example of a muzzle flash recording is given in Fig. 1. The spreadsheet included with this report illustrates this example and shows the analysis for the maximum range of probable visibility. The illuminance produced by an example flash 1 m from the muzzle is shown in Fig 1.

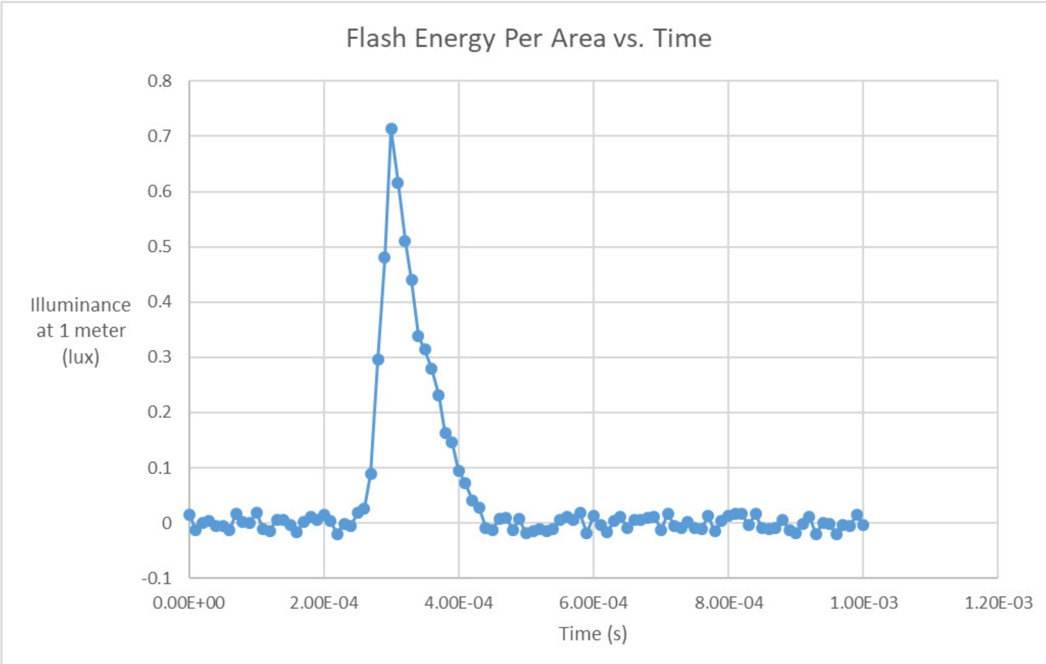

Fig. 1 Example of a muzzle flash recording

The total luminous exposure of this flash is given by the time-integral of the illuminance at the detector, which is given by

$$E_{flash} = \int_0^{T=total} E(t)\, dt \tag{2}$$

A trapezoidal integration is used in the spreadsheet. For the example shown, the total illuminous exposure is 4.8 E-2 mlux.s, measured at 1.0 m from the muzzle. For a quantity that describes the luminous energy, I_{flash}, of the flash in candela*seconds (cd*s) as opposed to the illuminance of a surface in lux, a simple conversion is based on the luminous energy source unit definition: 1 candela source produces 1 lux of illuminance at a distance of 1 m. Thus, the flash source strength, I_{flashs}, in candela is determined from the measured illuminance, E_{flash}, as

$$I_{flash} = E_{flash} \times R^2_{measurement} \tag{3}$$

where I_{flash} is in candela, E_{flash} is in lux (or lumen per square meter), and R is in meters.

Using the previous equation to predict the farthest distance away where this flash has a 50% probability of being seen by an attentive unaided human observer, the farthest probable visible distance is 52 m, in full darkness. This does not consider a viewer using vision aids like binoculars or night-vision equipment, and it assumes full dark adaptation with no background luminance. The spreadsheet includes estimated flash levels for visibility in different background lighting. Visibility thresholds have been estimated based on a constant ratio of background luminance to total luminous exposure. As an example, under starlight, the detection range is estimated to be 15 m; the shorter distance corresponding to greater background light under starlight rather than darker overcast night.

2.1.2 Ongoing Field Measurements

While threshold visibility is considered well established, the wide range of flash characteristics and viewing conditions cause uncertainty in the probability of seeing a specific weapon's flash under specific viewing conditions. Discrepancies between the visibility results of Hennage's and Hecht et al.'s work justify the need for additional field tests under conditions more relevant to the visibility of small arms flash in actual outdoor field conditions. These tests will better validate the appropriate flash visibility level, $E_{T.}$, for small arms fire in outdoor environments. Flash visibility values will be produced to measure background lighting levels, allowing visibility and maximum visible ranges to be determined for specific firearm stimuli, field-relevant background conditions.

We expect acuity to apply to the average visual detection threshold across the population. A direct interpretation of Snellen visual acuity applies to visual detection. A Snellen score of 20/40 means that the line the person reads correctly at 20 ft is read correctly by a person with normal vision at 40 ft: fundamentally twice the distance. Alternately, a score of 20/10 means the line the person correctly reads at 20 ft can only be read at 10 ft by a person with normal vision. In this case, half the distance. Thus, for people with visual acuities between 20/10 and 20/40, we expect the range of flash visibility to vary by a factor of 4.

While a specific range of certain nondetectability may be difficult to guarantee, a standard method for evaluating nondetectability ranges will produce useful relative rankings for evaluating flash suppression, even if the method provides only approximate operational guidance.

2.1.3 Visual Localization

For a visible flash, particularly a repeating flash, visibility provides excellent localization. We consider visualization of the flash to provide adequate and precise visual localization to support effective return fire. Since Snellen visual acuity is based on the angle subtended by the lines of the letters in the test chart, visual acuity will determine the localization potential for a visible flash. Localization to within 1 arc-min is common for people with normal vision.

Against an otherwise dark featureless background, after a single brief flash, or a series of repeated flashes, is no longer visible, uncertainty in the recalled direction of the flash is expected to increase with time. While increasing this uncertainty will restore stealth over time, we do not have plans to measure the rate of increase in localization error of a visible flash as a function of the time after the flash is no longer presented.

2.2 Stealth: Audition

2.2.1 Auditory Detection

Auditory detection is well modeled with the DEVCOM Army Research Laboratory Auditory Detection Model (ADM; Garinther et al. 1985). The model has been the basis of auditory nondetectability established in the MIL-STD-1474E Military Noise Standard for many decades. The model is based on the audibility of the Fourier components of a sound. Abouchacra et al. (2007) indicate that sound detectability is well approximated as long as the signal-to-noise ratio remains in the order of 0 dB, and the overall signal amplitude is above the hearing threshold of the listener. In the ADM, a signal sound is considered audible when the most detectible Fourier component is equal to, or greater, than the listener's hearing threshold plus the background noise component at the listener's position.

The ADM was validated in sound detection trials held at Aberdeen Proving Ground, Maryland (Fluitt et al. 2015). Fluitt et al. (2015) found the performance of human listeners was accurately predicted by the ADM to within the ability to determine environmental sound propagation conditions and measure background noise levels.

The ADM is applied by measuring the sound produced by a sound source at a specified distance from the source. This sound is decomposed into Fourier components in 1/3 octave bands, and each band is propagated to a distance where the sound amplitude in that band is at the threshold detection level for that frequency. The band that can be heard at the farthest distance establishes the detection range for the sound source.

The model includes several environmental propagation effects and has allowances for hearing loss among the listeners and differences in background noise levels at the positions of the listeners.

The model provides a detailed illustration of the sound detection process in the form of a graph showing each band at the detection range, the attenuation of the band during propagation and spherical spreading, hearing threshold levels, and aspects of signal detection in the 1/3 octave bands. Elements in the graphic model output are labeled in a picture provided by the model, as shown in Fig. 2.

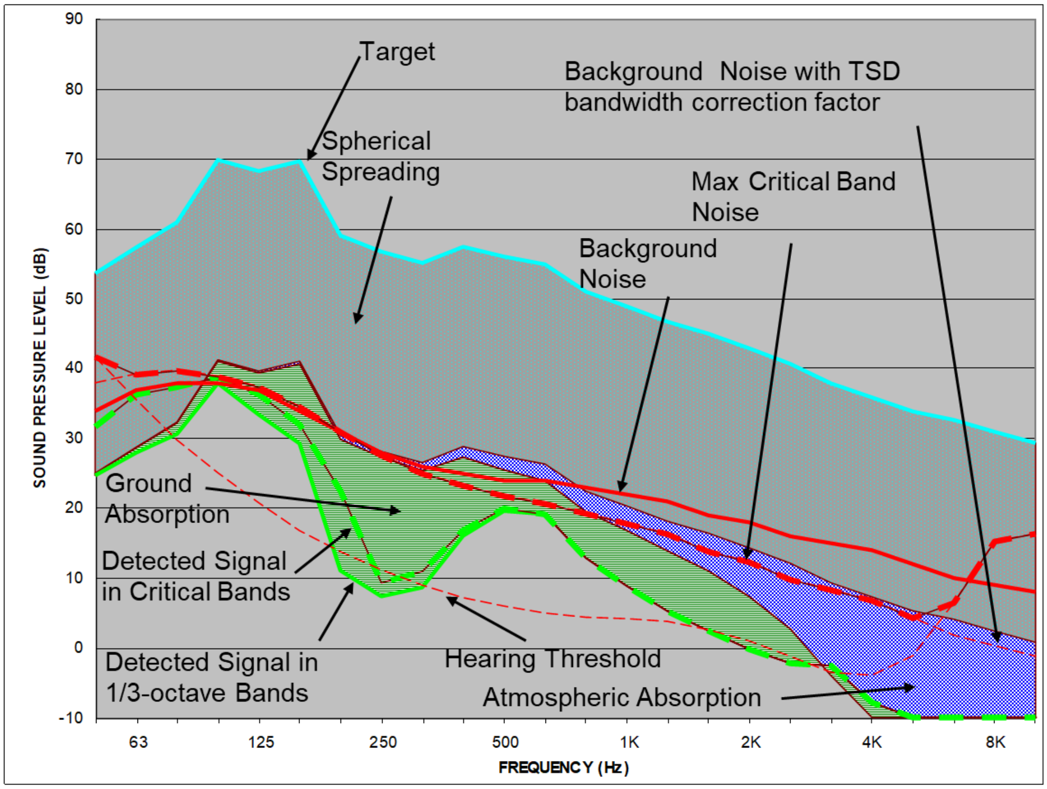

Fig. 2 Elements within the ADM output

The graph provides details of the sound propagation and detection process. The model produces a spreadsheet that also lists a table summary of the analysis, giving the overall target sound level (dBA), the maximum detected distance (m), the detected frequency band (Hz), the detected 1/3 octave band level (dBA), the overall detected sound level (dBA), and the overall background noise level (dBA).

The model does not label the components on the graph of the actual model results. The labels are presented on a picture of model output. The picture gives the user the information needed to place labels on the actual model output.

Using the spectra in Table 1, we demonstrate the ADM. The spectra were obtained from recordings of unsuppressed and suppressed M4 (5.56-mm) rifle fire gathered by Grasing (2013). These measurements are not necessarily what would be used in a field detectability assessment; we use them only to demonstrate the ADM.

Table 1 Spectra from recordings of unsuppressed and suppressed M4 (5.56-mm) rifle fire (Grasing 2013)

Band Number	Frequency Hz	Unsupp'ed Noise dB	Supp'ed Noise dB
1	16	81.98	74
2	20	83.77	75
3	25	85.61	76
4	31	87.35	77.32
5	39	88.36	78.98
6	50	91.25	80.63
7	63	97.12	82.85
8	79	103.1	87.25
9	99	106.77	89.76
10	125	106.65	88.74
11	157	109.32	88.55
12	198	115.23	91.49
13	250	115.23	89.68
14	315	118.17	90.13
15	397	119.83	91.29
16	500	121.66	90.11
17	630	119.61	85.01
18	794	118.39	85.49
19	1000	112.94	90.45
20	1260	115.89	88.39
21	1587	113.17	89.83
22	2000	112.83	89.76
23	2520	111.09	92.64
24	3175	108.26	91.17
25	4000	108.87	93.98
26	5040	107.88	93.53
27	6350	107.2	93.02
28	8000	105.13	89.63
29	10079	103.05	85.37
30	12699	103.49	88.62
31	16000	103.03	85
32	20159	100.56	83.87

In this example, the tables of detection results for unsuppressed and suppressed M4 are shown in Table 2. The analysis result for the unsuppressed weapon is on the left, and the analysis result for the suppressed weapon is on the left.

Table 2 Detection results for unsuppressed and suppressed M4

Target Level (dBA)	126.1
Detect Distance (m)	17796.9
Detect Frequency (Hz)	250.0
Detect 1/3 Oct Band Level	27.0
Detect Level (dBA)	21.5
Background Noise Level (dBA)	32.7
Target Level (dBA)	102.8
Detect Distance (m)	3099.6
Detect Frequency (Hz)	315.0
Detect 1/3 Oct Band Level	24.3
Detect Level (dBA)	24.5
Background Noise Level (dBA)	32.7

The background noise level in this example is the Environmental Protection Agency (EPA) rural noise level. This background noise level corresponds to the Level 1 – Rural Area Ambient Noise Level - specified in MIL-STD-1474E (DOD 2015). Level 1 is the higher of the two noise levels applied in MIL-STD-1474E for determining auditory nondetectability.

Figure 3 shows the sound profiles, attenuations, and levels for detecting the unsuppressed rifle fire. The detection distance is 17.8 km, and the detection occurs in the 250-Hz component of the unsuppressed muzzle blast.

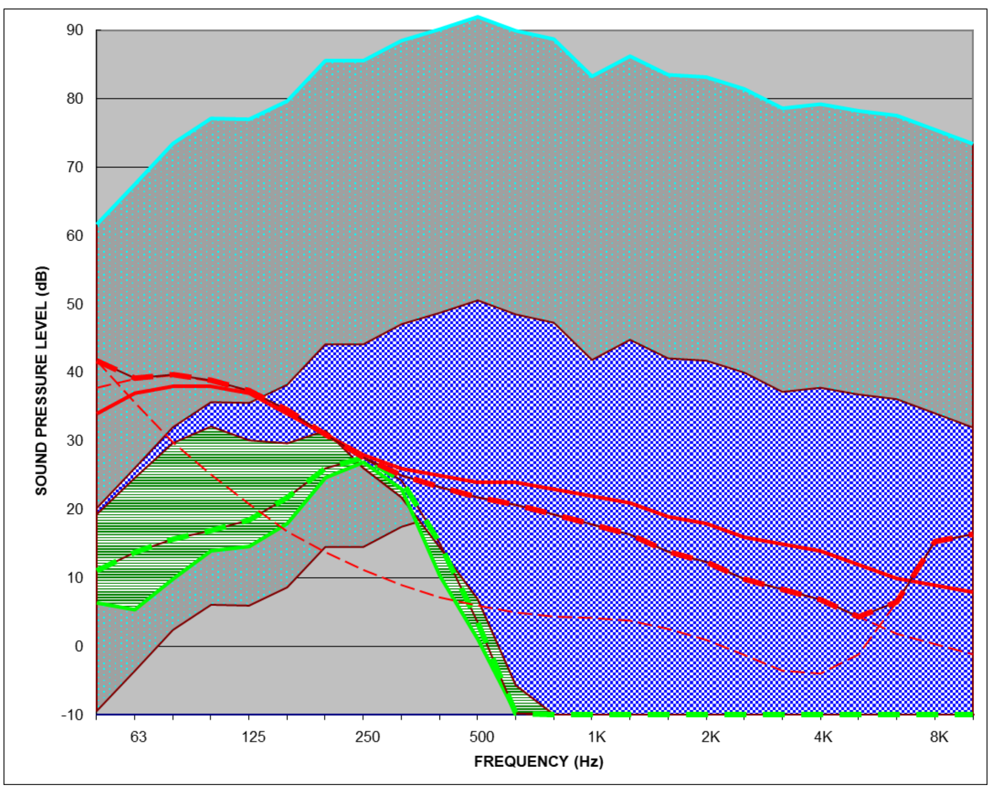

Fig. 3 Sound profiles, attenuations, and levels for detection of the unsuppressed rifle fire

Figure 4 shows the sound profiles, attenuations, and levels for detection of the suppressed rifle fire. The detection distance is 3.1 km, and the detection occurs in the 315-Hz component of the suppressed muzzle blast.

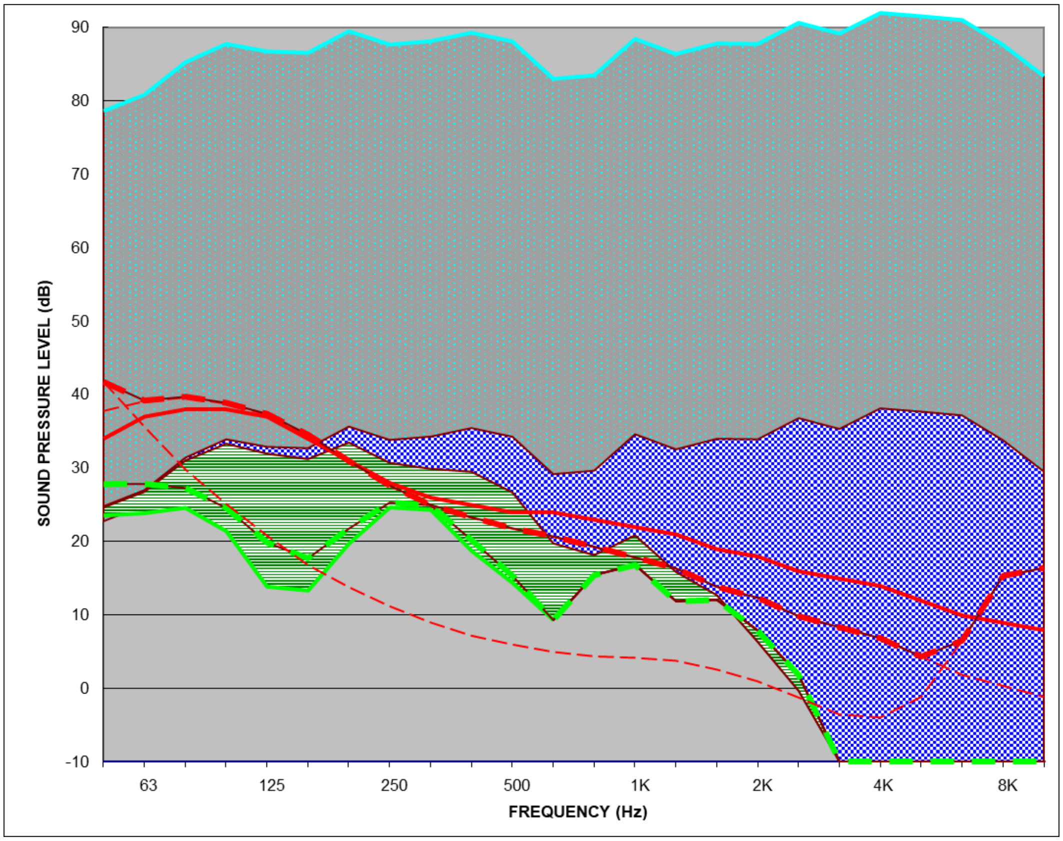

Fig. 4 Sound profiles, attenuations, and levels for detection of the suppressed rifle fire

The detection ranges in Figs. 3 and 4 are large. For a brief covert small arms engagement, MIL-STD-1474E aural nondetectability criteria may not provide the best assessment. While a small arms discharge might be detected, if it is gone in a brief moment, there is less chance to further investigate the noise, localize it, identify it, and respond to it. Even when a rifle shot could be detected up to 17 km, it is quite possible that the sound would not be identifiable as gunfire and would not alert enemy combatants.

MIL-STD-1474E and the ADM make several assumptions regarding auditory detection. They assume sounds are continuous, they assume listeners are alert to when a sound occurs, they assume low background noise levels that may not apply in many situations, and they assume a constant environmental condition over the entire sound propagation distance. While the ADM was validated with brief noises, its application in MIL-STD-1474E assumes sounds are presented for times long enough to further investigate the sound. Noise from a generator or vehicle on the other side of a hill or wooded area could be detected, localized, and investigated further, even if it was not immediately identified. Thus, a conservative basis for aural nondetectability is necessary for continuing operations, but this may not apply to isolated gunfire. In validating the ADM, listeners were told when the sound would be presented; they were alert and concentrating on hearing a sound. Again, this may not apply to isolated gunfire.

In addition, environmental conditions can significantly vary over many kilometers. Atmospheric temperature profiles and terrain features may vary locally over the distance of propagation and refract sound away from listener positions. Potential listeners may be engaged in other auditory tasks. Noise may be greater than the Level 1 Rural Area Ambient Noise Level; the Level 1 values may not be the most representative of operational conditions for isolated gunfire.

Garinther et al. (1985) concludes, "The background noise level at the listener's location is probably the single most important factor for determining aural nondetectability(sic)." We have examined the noise assumptions used in the standard and performed subsequent analyses to see how detection distances vary with additional noise levels.

Background noise levels in MIL-STD-1474E represent quiet environments. Level 1 noise represents a rural setting about 4 km from the nearest traffic noise, and Level 2 noise represents a very quiet environment, located about 16 km from the nearest traffic noise. These backgrounds are shown in 1/3 octave bands in Fig. 5.

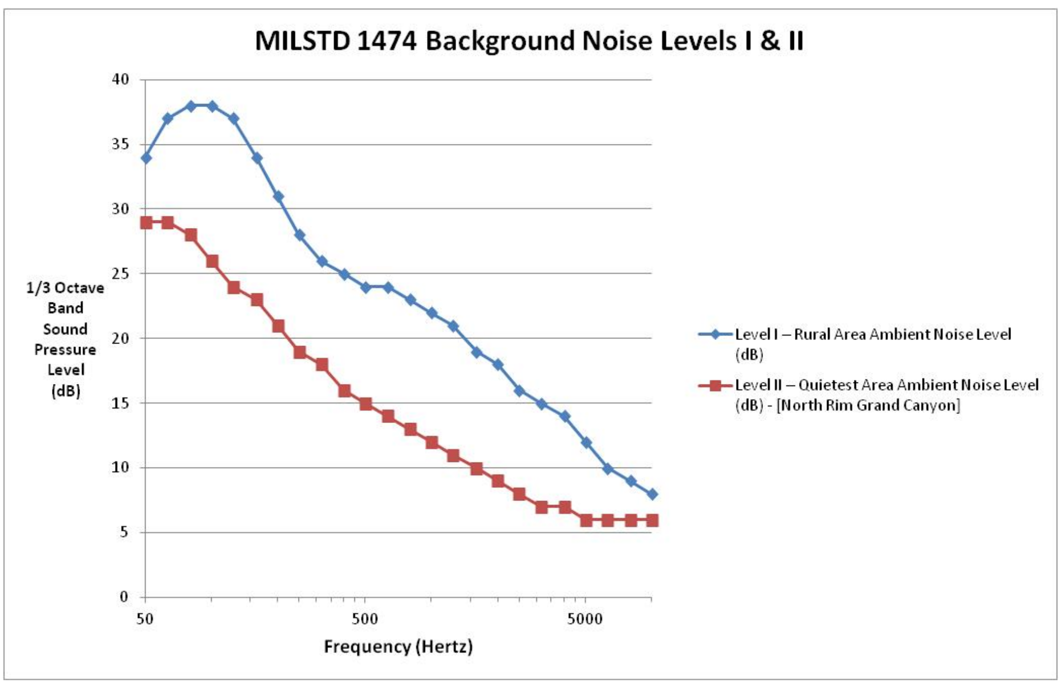

Fig. 5 Background noise level, shown in 1/3 octave bands

The background sound levels used in MIL-STD-1474E came from an EPA study of background noise levels across the United States (Eldred 1971). The quietest place found in the study was the North Rim of the Grand Canyon. The second quietest place was a rural farm valley. A background noise study was also conducted in the State of Illinois. Background sound levels in the Illinois study are available from Bonvallet (1951) and Harris (1991).

Sound levels in the Illinois study are compared with the EPA sound levels in Fig. 6.

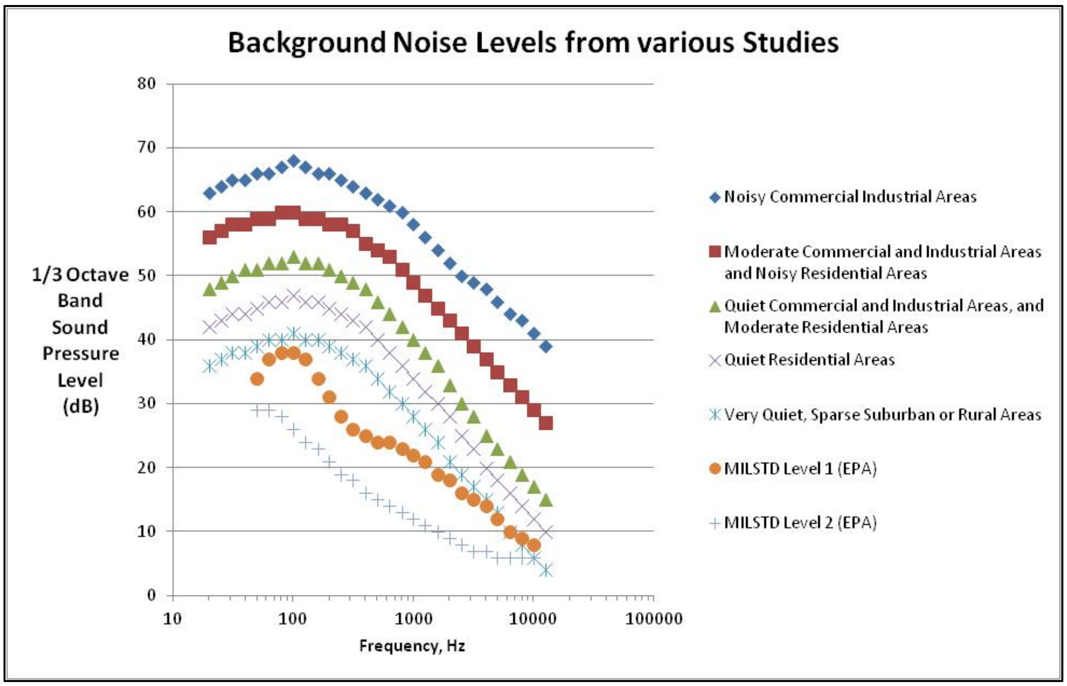

Fig. 6 Comparison of sound levels between the Illinois study and EPA sound levels

Figure 6 shows that the EPA noise levels are lower than the noise levels in other background noise studies, especially in the frequency bands in which small arms fire might be near threshold detection levels, which are shown in the ADM graphic outputs to be between 200 and 800 Hz. It is possible that the sound background levels used in MIL-STD-1474E may not be the most appropriate background levels for assessing the detectability of small arms fire.

To examine how different noise backgrounds can influence the range of detection of gunfire, we considered different levels of background sounds and determined the gunfire detection ranges that each of these background sounds implies. The background levels chosen for this analysis are shown in Fig. 7.

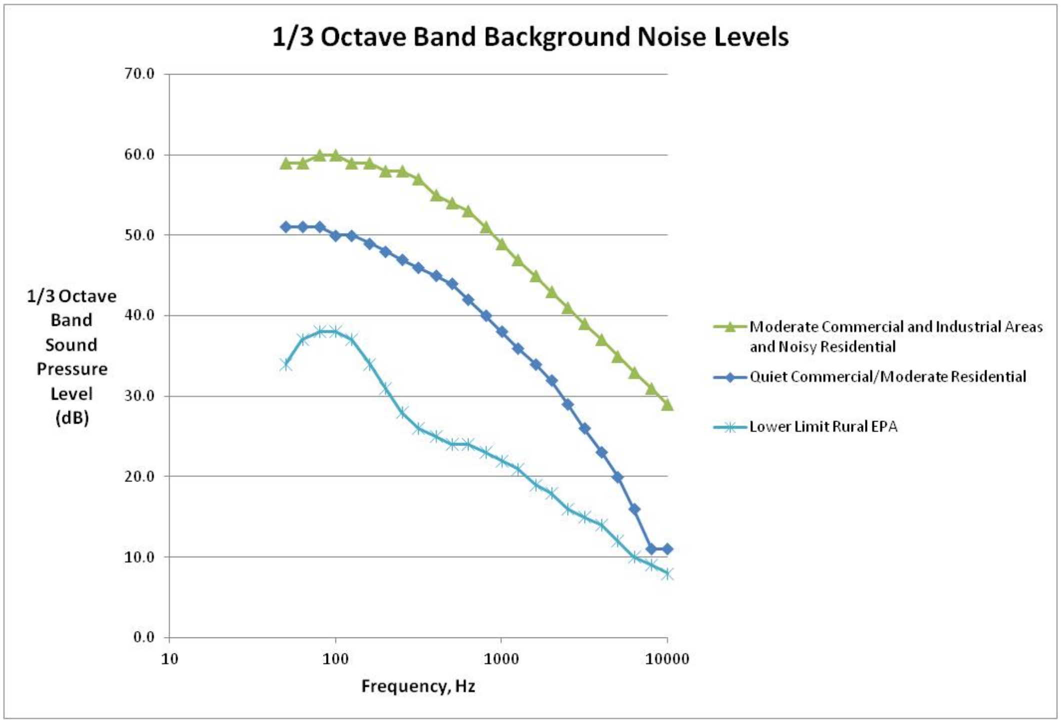

Fig. 7 Background sound levels chosen for this analysis

Using the suppressed and unsuppressed gunfire recordings provided by Grasing (2013), we reevaluated the detection ranges for three levels of noise backgrounds (Table 3). We have included the Level 1 noise background from MIL-STD-1474E and two background levels from the Illinois study: the Quiet Commercial/Moderate Residential noise level and the Moderate Commercial and Industrial and Noisy Residential level.

Table 3 Average detection ranges for three levels of noise backgrounds

Noise level	Unsuppressed Detect distance (m)	Suppressed Detect distance (m)
Lower limit rural EPA	17000	3000
Quiet Commercial/Moderate Residential	4900	940
Moderate Commercial and Industrial and Noisy Residential	2700	467

Direct application of the MIL-STD-1474E auditory nondetectability assessment and the ADM, even with some elevated noise levels, may not directly translate to operations. However, by gathering field test results in measured conditions and assessing operational noise conditions and likely listener alertness, ADM results can be empirically adjusted to provide an operationally relevant measure of the effective auditory nondetectability range for suppressed and unsuppressed small arms auditory muzzle blast stimuli.

2.2.2 Auditory Localization

If muzzle blasts were successfully suppressed to levels providing desired nondetectability ranges, enemy combatants and listeners would still hear the ballistic cracks of bullets with the supersonic speeds necessary for effective long-range engagements. However, as we show, the ballistic crack may be a miss-leading cue toward auditory localization of the actual shooter's position.

Humans with normal or near-normal hearing localize sounds using binaural sound cues. The localization process is primarily based on the interaural time difference and the interaural level difference (Wightman and Kistler 1992; Blauert 1997). Auditory localization has been the subject of research for over 100 years (Young 1928).

2.2.3 Front–Back Reversals

Human auditory localization is subject to front–back confusion across the interaural axis, as illustrated by Pulkki (2001). Sounds originating anywhere on the cone of confusion, which has a vertex at the ear and a central axis along the interaural axis, produce the same interaural time difference, thus leading to possible front–back reversals for sounds in the azimuthal plane. Scharine (2009) reports that most large localization errors are due to confusion associated with front–back reversals. Pulkki (2001) also notes these reversals can be resolved by head movement and spectral cues but notes these cues are not always effective. For repeating impulsive sounds, head movement can resolve front–back reversals, but for a single isolated impulsive sound, head movement is not likely during the duration of the sound.

If sounds are anticipated from the direction of probable enemy contact and sound sources are reduced to a likely half-space, reversals are not likely. While combat personnel may not know exact enemy locations, they extend considerable effort ensuring that the enemy is in a known half-space direction and is not behind them. As a result, we do not consider reversals in assessing how humans auditorially localize gunfire. We assume observers know that gunfire is coming from a known half-space direction.

2.2.4 Environmental Influences

The ability to localize sounds is influenced by the environment. Frequency-dependent reflection and attenuation both influence localization cues. Dobbins and Kindick (1967) report impulse localization accuracies in the range 13° to 36° azimuth error. Abouchacra et al. (2007) indicate humans can localize impulsive sounds to within ±15° approximately 80% of the time when signal and noise amplitudes are equal. Auditory localization provides some indication of the direction the sound came from and is expected to cue a search for other visible stimuli. While auditory localization ability may not be sufficient for establishing effective return fire, it is sufficient to establish an angle of regard about the shooter location that will allow visual detection of flash or disturbed earth when these visible stimuli are present.

2.2.5 Precedence Effect

Most environments produce echoes arriving at a listener position various times after the direct non-echoed sound. The precedence effect (Wallach et al. 1949; Divenyi and Blauert 1987; Blauert 1997; Blauert and Braasch 2005) supports localization of sound sources by reducing the influence of delayed sounds in the perceptual localization process and reinforcing the perceived sound directions as originating from the direction of arrival of the first-arriving wavefront. This process is referred to as the precedence effect or Blauret's Law. Collective research also describes the echo threshold and shows that brief sounds from locations arriving no more than 10 ms apart are perceived as a single sound originating from a direction between the two sound origins. Hartung and Trahiotis (2001) create a filter model for the precedence effect, basing the model on laboratory tests with speakers and brief sounds. Blauert and Braasch (2005) show the precedence effect applies to sounds separated by less than about 80 ms and concludes that sounds separated by more than 80 ms are normally perceived as two separate sounds, placing a separate sound discrimination threshold at 80 ms.

In a detailed review article, Brown et al. (2015) gather experimental results showing a wide disparity between echo perception thresholds and separate sound discrimination thresholds, depending on the characteristics of the sound. Collected research results show echo thresholds can be as large as 83 ms, and the suppression of localization cues from the precedence effect can continue for times as long as 900 ms when stimuli are in reverberant environments and show longer durations.

In terms of small arms auditory stimuli, the difference between the arrival of a ballistic crack and the arrival time of a muzzle blast will depend on bullet speed and on the distance between the shot location and the listener. At a distance of 300 m downrange and near the shotline, arrival time differences can be 500 to 700 ms, depending on bullet speed. With reverberant echoes of the ballistic crack and the muzzle blast, we expect the precedence effect to dominate auditory localization, placing the perceived auditory source in the direction of arrival of the ballistic crack, which is the first-arriving wavefront.

This behavior was observed by Garinther and Moreland (1966) in a limited study involving shots fired from within an anechoic chamber. The chamber fully suppressed the audibility of muzzle blast to listeners that were located downrange. Participants were located 230 m downrange and 100 m to the shooter's left of the shotline. In this study, any possible localization influence from a muzzle blast was not present.

Garinther and Moreland report:

> Data were obtained from 29 naive Ss who had had basic training and one or two years of infantry training, but no combat. They were blindfolded outside the range area, then driven one at a time onto the range to points F and G (Fig. 9), where they were seated, still blindfolded. The weapon was fired from point B. They were given only the following instructions, and no more: "This is a listening test. We want you to try and locate and identify a noise. I'll let you know when to listen." After the shot, the S was asked (a) to point to the noise, and (b) to identify it. After answering these questions, the S was told he would hear the noise a second time. Again he was asked to point to it and identify it. After answering these questions a second time, the S was told that the noise he had heard was the ballistic crack of a flying bullet. He was told that the shot would be fired again and that this time he should "try and locate the shooter."

They continue to describe observations:

> When the Ss were 100 meters to the left of the trajectory, they reported that the noise source seemed to be in a direction perpendicular to the plane of shock wave. When the Ss were told that this was the noise of a bullet in flight and asked to locate the shooter, they replied that the shooter was in the direction of the noise. In other words, at Position G, the Ss thought the shooter was in a direction perpendicular to the shock wave's plane. At Position F there was confusion, but it is interesting to note that the Ss never really knew where the shooter was.
>
> It is also interesting to note all of the Ss thought the "ballistic crack" of the projectile was actually the muzzle blast from the gun. When told that the noise was the crack of a bullet in flight, many commented, "Yes, that's right, I heard the gun go off over there." Usually, the Ss would point toward the sound of the ballistic crack.

Auditory small arms stimuli may give misleading cues to the direction of the shooter, and the precedence effect may obscure directional information in any later-arriving muzzle blast; visual stimuli have been shown to significantly influence the perceived direction of sound origination. Hairston et al. (2003) report an unexpectedly large influence of visual stimuli on localization of sound sources. Wallace et al. (2004) show that visual stimuli influence the direction of perceived sound origination even when the stimuli are separated in time by as much as 800 ms, and sounds can be perceived as co-located with visual stimuli even when separated by 15°. Bishop et al. (2012) report multiple timescales in the process of sound localization due to the precedence effect, beginning between 70 and 100 ms, and cascading into visual influences of echo suppression lasting 500 ms. These time durations of echo suppression and the visual cue biasing of sound source localization are well within the ranges needed to influence the perceived direction of a shooter.

2.2.6 Auditory Localization Model

Based on the research cited above, auditory localization of small arms stimuli is expected to be in the direction of the first-arriving wavefront. For likely downrange enemy locations, the first-arriving wavefront will be the ballistic crack. Figure 8 shows the process.

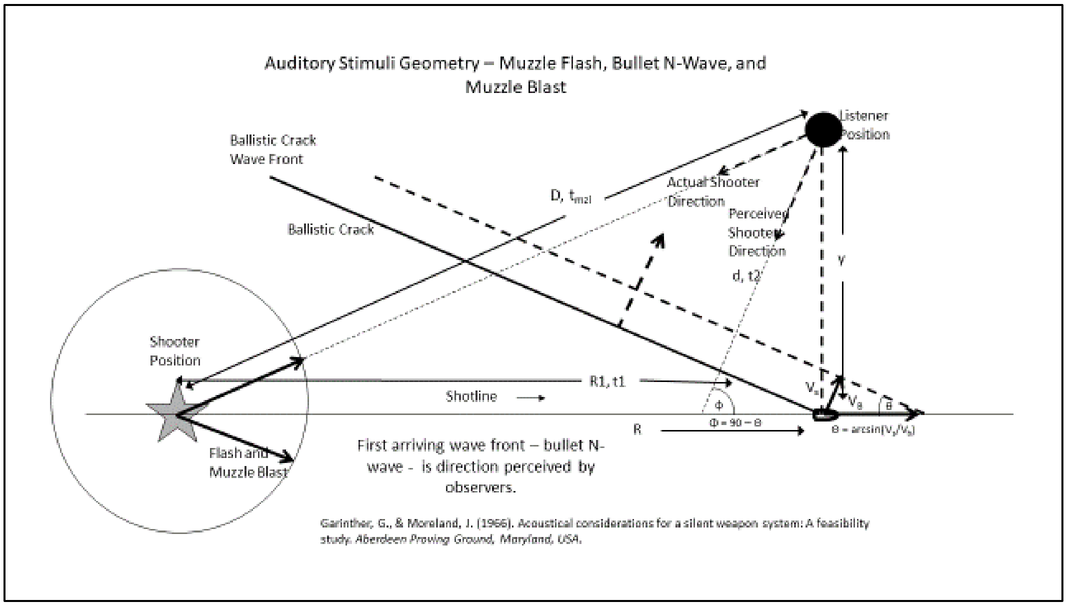

Fig. 8 Auditory localization of small arms stimuli

The angle between the wavefront of the ballistic crack and the shotline, θ, is

$$\theta = \arcsin\left(\frac{V_S}{V_B}\right) \tag{3}$$

This expression applies when the speed of the bullet, V_B, is greater than the speed of sound, V_S. Other parameters used to determine the arrival direction of the ballistic crack are shown in Fig. 8.

The angle, θ, must be determined at the point along the shotline where the bullet creates the ballistic crack that first reaches the listener. The bullet speed decreases as it moves along the shotline. This speed decrease changes the angle between the ballistic crack wavefront and the shotline.

We model the propagation of the ballistic crack from the shotline to the listener using a variational method (Cline 2017). The approach minimizes the total time it takes the ballistic crack to reach the listener after the shot is fired. As a simplifying approximation, we assume the bullet loses speed in proportion to the distance it has traveled downrange; the change in bullet speed per unit distance traveled is constant. The Blast-Crack model (Oberlin and Cler in prep) gives rates of speed decrease per unit distance traveled for many caliber bullets and many weapons.

The variational process is shown in Fig 9.

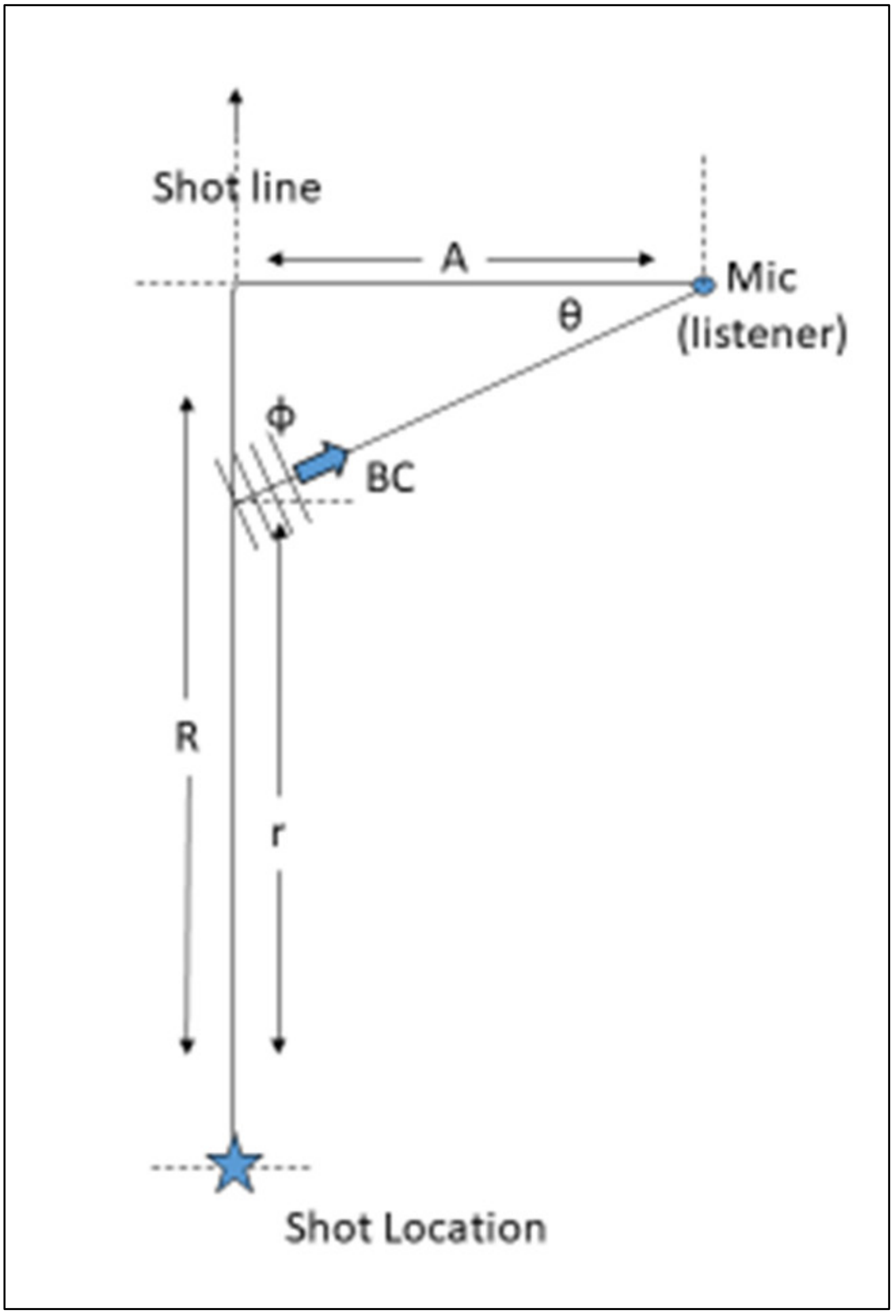

Fig. 9 Propagation of the ballistic crack from the shotline to the listener using a variational method

The variational process can be understood by considering that the bullet releases an incremental spherical component of the ballistic crack at each point along the shotline. Naturally, these components add to form the ballistic crack wavefront. Components released very early must propagate to the listener at the speed of sound; the bullet is faster, so components released further downrange will arrive earlier. Components released at the downrange distance to the listener (R) must propagate to the listener along a path perpendicular to the shotline. A wave component going along a slight diagonal will need to propagate nearly the same distance but can be released earlier than the component released exactly at the perpendicular downrange distance. Thus, the diagonal path has a shorter arrival time. The variational process finds the minimum time, giving the time and path of the part of the ballistic crack that arrives at the listener's position.

Adding the time it takes the bullet to reach a distance, r, along the shotline and the time it takes the ballistic crack, traveling at the speed of sound, to reach the listener along the diagonal path, we obtain a functional expression of the time required for the ballistic crack components to reach the listener. Minimizing this function gives the following implicit expression for the distance along the shotline where the ballistic crack reaching the listener is released. The expression is

$$r = R - \frac{A}{\left[\left(\frac{V_0}{c}\right)^2\left(1-\frac{\alpha r}{2V_0}\right)^4 - 1\right]^{\frac{1}{2}}} \tag{4}$$

This implicit expression can be solved iteratively, starting with the left-hand side r-value when α is zero and repeating the calculation with the actual value of α by using the left-hand side r-value in the right-hand side to produce the next iterated r-value. Note this process will produce a negative r-value for points sufficiently far from the shotline. Negative r-values indicate that the ballistic crack does not reach that across-range and downrange point.

Using r-values and ballistic crack arrival angles calculated for various down- and across-range points, a plot can be made showing the line of arrival of the ballistic crack at selected points on the field. Such a plot is shown Fig. 10.

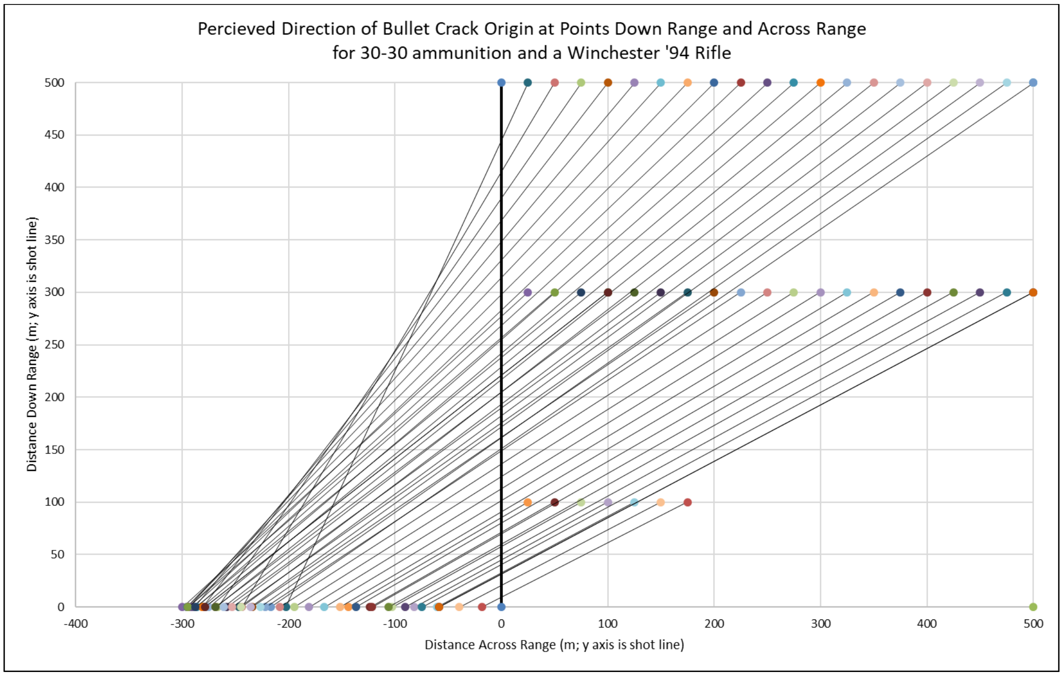

Fig. 10 Line of arrival of the ballistic crack at selected points on the field

This graph shows, as the bullet loses speed, the apparent direction of the arriving ballistic crack can wrap back for points closer to the shotline. These lines show the direction of arrival of the ballistic crack at various down- and across-range points, and they also indicate the generation point along the shotline where the ballistic crack originates for arrival at each down- and across-range position.

The ballistic crack represents the first-arriving waveform for a significant portion of likely enemy locations down and across range. In this example, for a downrange distance of 100 m, the ballistic crack is the first-arriving wavefront at distances within about 195 m of the shotline. At distances further from the shotline, the muzzle blast will be the first-arriving waveform. While auditory localization from these further distances is expected to be centered on the actual location of the fired shot, we assume the most likely enemy locations will be closer to the shotline, where the ballistic crack is the first-arriving wavefront.

The graph in Fig. 10 shows the predictions of the auditory localization model. The uncertainty in directional localization of impulsive sounds and the disparate angle between the arrival of ballistic cracks and any subsequent perception of muzzle blasts indicate that the direction of a shooter will generally be misperceived when based only on auditory stimuli.

Visual stimuli, occurring within 500 to 700 ms before, repeatedly occurring during the arrival of the ballistic crack, will dominate the auditory directional perception, even if the location of the visual stimuli is not the actual location where the shot was fired.

2.2.7 Ongoing Field Measurements

With muzzle blasts from unsuppressed and suppressed weapons using practical small arms suppressors, field tests are planned to precisely determine auditory localization perception. Data from these field tests will be used to empirically fit and/or validate auditory localization based on the precedence effect. Combinations of flash stimuli at locations other than the actual shooting location also would help determine if false flashed aligned with the ballistic crack would form a more compelling perception of shooter location than flashes at the actual weapon location.

2.2.8 Acoustic Sensor Localization of Gunshots

Acoustic sensors have been used for localization of sound sources for many decades (Mattei et al. 1960). Sensors for localizing sound generally rely on an array of detectors, typically involving a minimum of three (Liu et al. 2009). Law enforcement applications of equipment for sound stimuli localization of gunshots in American cities are reported by Mazerolle et al. (1998) and Ratcliffe et al. (2019). They report unsuccessful gunshot localization in cities generally described as complex echoic environments. A triple-signal, dual mechanically coupled sensor system has been proposed by Liu et al. (2009). This system derives sound direction based on the phase difference between two closely spaced and mechanically coupled tympanic-like membranes. This system is inspired by the remarkable sound localization capabilities of the parasitoid fly *Ormia ochracea* (Miles et al. 1995). We do not know of an equivalent mechanical process that has been used successfully to date.

2.2.9 Speech Communication

Auditory speech communication capability was quantified by Fletcher (1921) as the articulation index. The articulation index was established to quantify the speech transmission capabilities of telephone communication. The articulation index is described in a Siemens Digital Industries Software Community Article (Mila 2019). The articulation index is calculated in a 30-dB range above the lowest understandable hearing level in the 1/3 octave frequency bands used in human speech. The 30-dB range for the articulation index gives an upper limit of speech amplitude considered appropriate for use over telephone communication systems. Figure 11 shows the articulation index amplitudes.

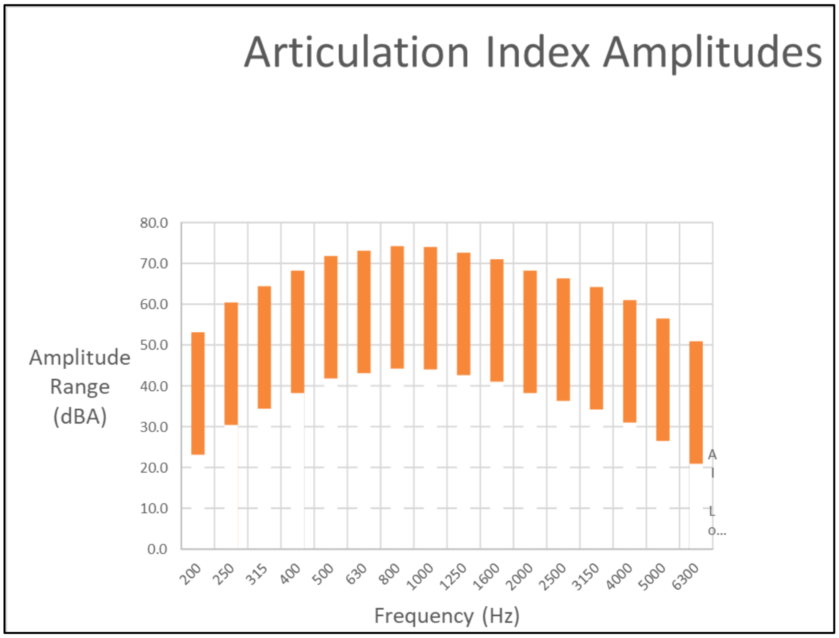

Fig. 11 Actuation index amplitudes

The area represented by the bands in Fig. 11 determines the articulation index when the length of each band is multiplied by a factor determined by the importance of that band in human speech communication. The values used to calculate the articulation index are shown in Table 4 (Mila 2019).

Table 4 Values used to calculate the articulation index

Band Number	1/3 Octave Center Frequency	AI Lower Level dBA, L(low) (dBA)	AI Upper Level, L(high) (dBA)	Speech Weighting Factor
1	200	23.1	53.1	1
2	250	30.4	60.4	2
3	315	34.4	64.4	3.25
4	400	38.2	68.2	4.25
5	500	41.8	71.8	4.5
6	630	43.1	73.1	5.25
7	800	44.2	74.2	6.5
8	1000	44.0	74.0	7.25
9	1250	42.6	72.6	8.5
10	1600	41.0	71.0	11.5
11	2000	38.2	68.2	11
12	2500	36.3	66.3	9.5
13	3150	34.2	64.2	9
14	4000	31.0	61.0	7.75
15	5000	26.5	56.5	6.25
16	6300	20.9	50.9	2.5
			Total:	100

The weighting factor determines each band's contribution to the articulation index. The articulation index is calculated as

$$AI = \sum_{n=1}^{16} \left(\frac{[L(high) - L(low)]}{30}\right) w_f \tag{5}$$

When noise does not obscure this range, the articulation index sums to 100%.

Noise can obscure portions of the bands shown in Fig. 11. Using a convenient X, Y line graph, the articulation index bands are shown in Fig. 12, with an arbitrary example of a noise spectrum added to the lower hearing threshold levels.

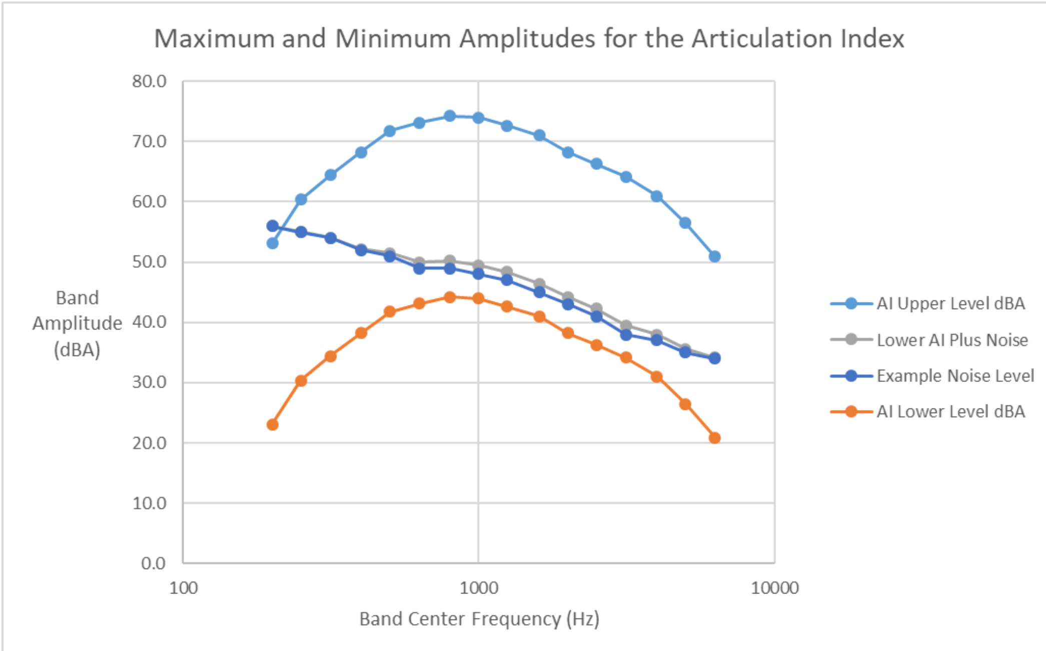

Fig. 12 Articulation index bands. Also shown for comparison is an arbitrary noise spectrum.

In this example, the articulation index is reduced to 73.7% by the noise. When the noise pushes the lower level above the upper level of the articulation index, that band contributes nothing to the articulation index. It does not contribute a negative value. Figure 12 shows the noise spectrum and the spectrum of the noise summed with the lowest level of the articulation index. Because the amplitudes are given in decibels, when sound decibel levels are added, the sound level is nearly equal to the larger sound value, unless the sounds are within only a few decibels of each other.

The articulation index was created to describe the quality of speech communication over telephone systems. A telephone system that required screaming was considered to have no quality. The ADM gives a level of 82.4 dB to shouting human speech. However, the loudest human voice is reported to reach 129 dB (Janela 2014). Hacki (1999) reports high human voice levels between 106.5 dB (female) and 108.5 (male). Rostolland (1982) reports a 70-dB rise from a normal spoken voice to shouted two-syllable words. We estimate an upper-bound voice amplitude for military field shouting to be 107 dB. This level is produced by a 25-dBA increase above the shouting level cited in the ADM. Using a 25-dB increase in the upper level of the articulation index gives a shouting articulation index (S-AI) range of 55 dB, rather than 30 dB. The upper and lower range of our estimated S-AI are shown in the graph in Fig. 13.

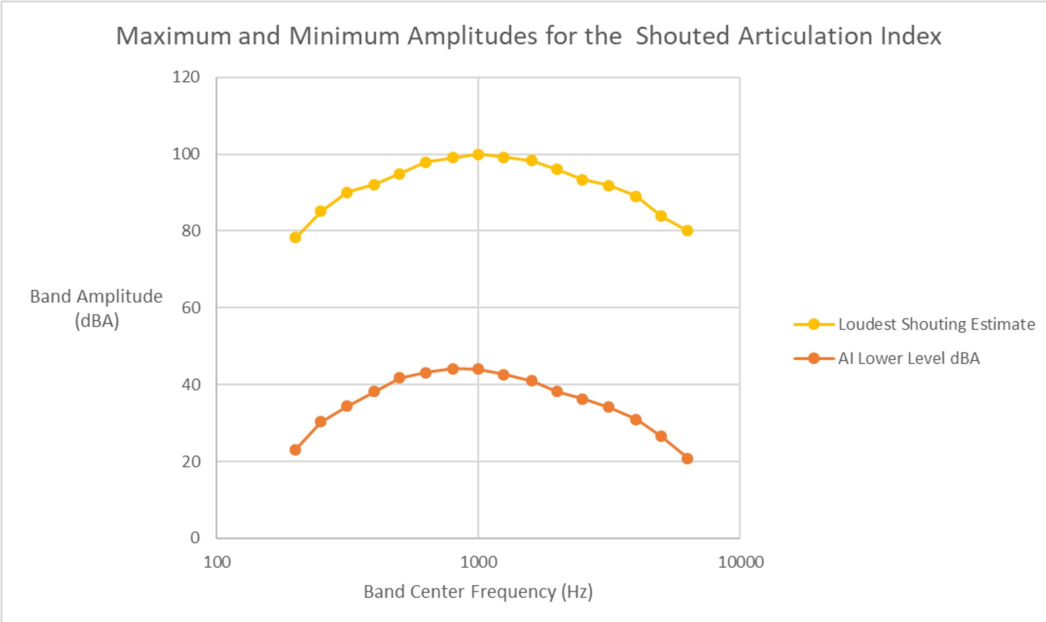

Fig. 13 Upper and lower range of our estimated S-AI

This large amplitude range may not represent communication with a full complement of vocabulary words. It also probably could be experimentally shown to have different frequency importance values than those values used in the lower-amplitude speech communication. Although we have raised the upper volume of the S-AI to very loud shouting, we have retained the importance factors associated with the frequency bands of the articulation index We have not expanded consideration to include possible differences between the importance factors of the different articulation index frequency bands and how frequency importance may vary for the few shouted commands in shouted communication.

The S-AI is calculated as

$$S\text{-}AI = \sum_{n=1}^{16} \left(\frac{[L(high)-L(low)]}{55}\right) w_f \tag{6}$$

We illustrate how the S-AI is applied. Grasing (2013) measured suppressed and unsuppressed firearm muzzle blasts using the forerunner of the NATO suppressor muzzle blast measurement procedure. The recording location was not where muzzle blasts would be measured for communication effectiveness, but we apply Grasing's measurements here to illustrate S-AI calculations for firearms.

Table 5 gives 200-ms time-weighted average 1/3 octave band levels for a suppressed and an unsuppressed muzzle blast at the 1/3 octave bands used in the articulation index. These are taken from Grasing (2013).

Table 5 The 200-ms time-weighted average 1/3 octave band levels for a suppressed and an unsuppressed muzzle blast at the 1/3 octave bands used in the articulation index (Grasing 2013)

Band Number	1/3 Octave Center Frequency	Unsuppressed Muzzle Blast Example (dBA)	Suppressed Muzzle Blast Example (dBA)
1	200	115.23	91.49
2	250	115.23	89.68
3	315	118.17	90.13
4	400	119.83	91.29
5	500	121.66	90.11
6	630	119.61	85.01
7	800	118.39	85.49
8	1000	112.94	90.45
9	1250	115.89	88.39
10	1600	113.17	89.83
11	2000	112.83	89.76
12	2500	111.09	92.64
13	3150	108.26	91.17
14	4000	108.87	93.98
15	5000	107.88	93.53
16	6300	107.2	93.02

Plotting these on the S-AI band amplitude graph gives the graph in Fig 14.

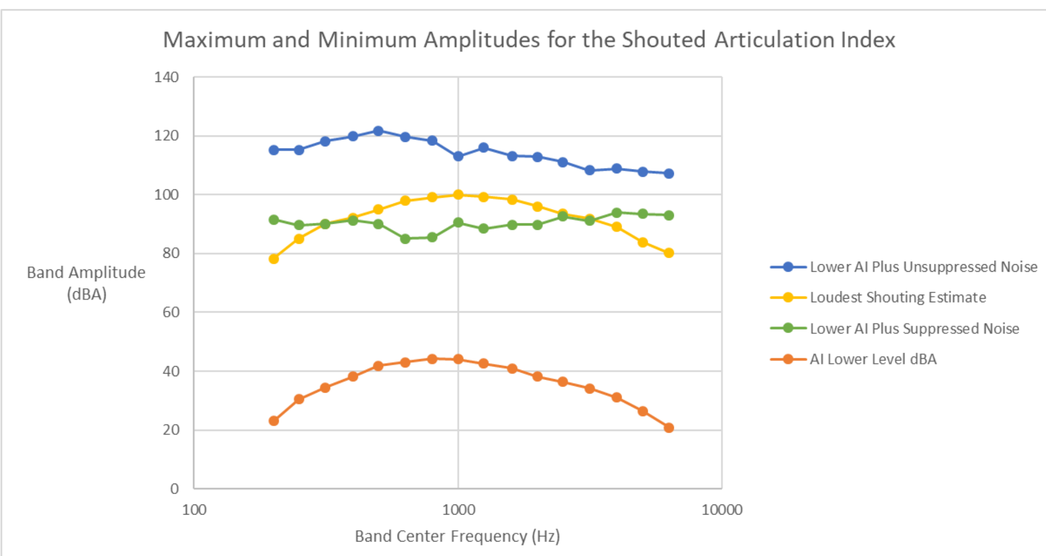

Fig. 14 Minimum and maximum amplitudes for the S-AI

The unsuppressed muzzle blast clearly obscures the entire channel. The S-AI for unsuppressed noise levels is zero. The unsuppressed muzzle blast clearly leaves available some shouted communication channel. Using the previous expression for the S-AI for the suppressed muzzle blast noise, we get a value of 9.5%. Recall when the noise is over the upper bound, the contribution is zero; it is not negative. While 9.5% is not large, it does indicate possible voice communication of limited commands, perhaps reflecting the shouted two-syllable words studied by Rostolland (1982).

2.2.10 Environmental Awareness

Allen (2005) showed the articulation index is mathematically equivalent to a Shannon information channel capacity. Shannon had described information communication earlier (1948) and updated this description more recently (2001). Given the importance of frequency components of speech and the amplitudes of voice, the articulation index represents a quantitative measure of the speech information that can be passed through the human auditory channel. The articulation index represents the speech information transfer capacity of the auditory modality.

Environmental auditory awareness has not been investigated to the extent applied to voice communication. The survival and threat characteristics of sounds have not been as extensively researched as the information content of speech. However, deriving the importance of the auditory channel from its evolutionary development in contributing to the survival of the individual, we hypothesize the ability to hear across the entire auditory channel is beneficial to survival. Increased survival probability has driven the overall auditory channel to a total capacity suited for survival. Although research could be performed to better detail how different frequencies and different amplitude ranges might contribute to Soldier survivability, in the absence of this research, we propose to evaluate a component of suppressor benefits based on how much of the total auditory channel is left unobscured by suppressed and unsuppressed muzzle blasts. Thus, the weighting factors applied to the frequency bands in assessing the speech communication channel capacity are all set to unity.

Although further information on amplitude and frequency significance could be obtained in the future, we offer the following evaluation of suppressor influences in auditory environmental information awareness.

Following the description of the total auditory channel given by the Siemens Digital Industries Software Community Article (Mila 2019), we show the full auditory channel in Fig. 15.

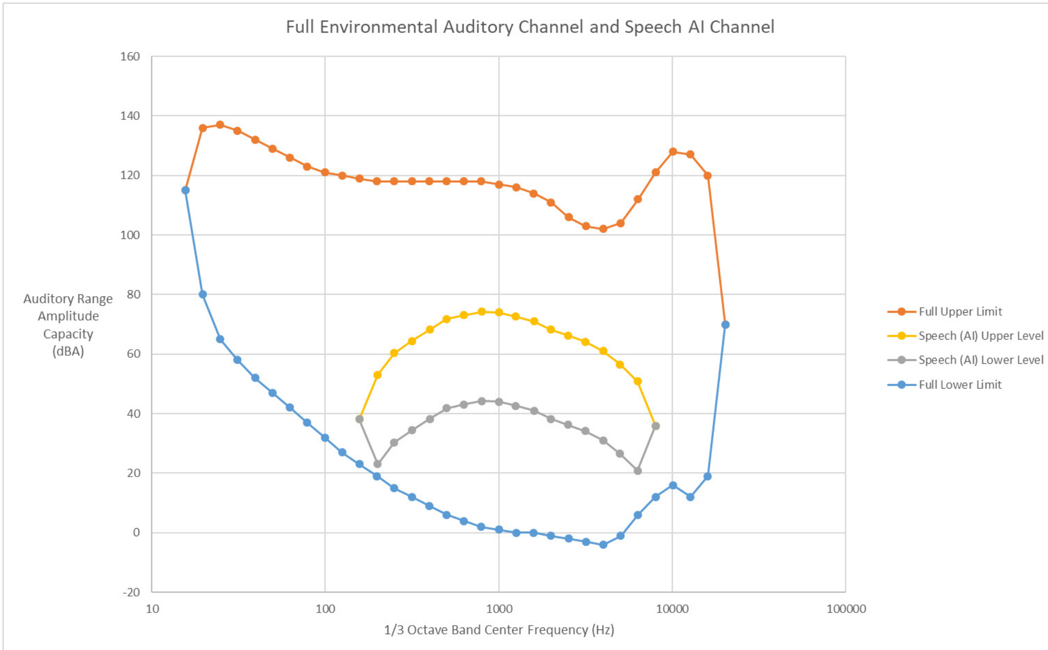

Fig. 15 Full auditory channel

For reference, the articulation index channel is also displayed. To close both the full channel and the articulation index channel, we have added points of area closure at the upper and lower frequency limits, so the upper maximum limit and the lower hearing threshold limit meet to show a finite bounded channel.

In analogy with the articulation index, the differences between the upper and lower limits represent the amount of information transfer capacity offered by each frequency band when no interference is present. When no noise is present, summing the difference between the upper and lower limit, divided by the difference between the upper and lower limit, simply gives the total number of bands.

Recall in the 16- and 20.2-kHz bands, the upper limit equals the lower limit, so these bands do not contribute to information transfer. The total across the other bands is 30. Recall we have no difference in weighting of those 30 bands, so 30 represents the full channel capacity for auditory environmental awareness. We have no information regarding the relative importance of one band over another for auditory environmental awareness, so all bands contribute the same amount when no obscuration is present. Without obscuration, the total auditory environmental awareness channel (AEAC) is 30.

When noise is present or when attenuating hearing protection is being used, a portion of this channel will be obscured. The lower limit becomes the level of the hearing threshold plus the level of the noise spectrum, or plus the attenuation of the hearing protector attenuation. In addition, hearing loss also raises the lower limit, obscuring a portion of this AEAC.

Taking muzzle blast spectra from Grasing (2013), we plot the sum of the hearing threshold (full lower limit in Fig. 15) and the spectra of the suppressed and unsuppressed weapon recordings in Fig. 16.

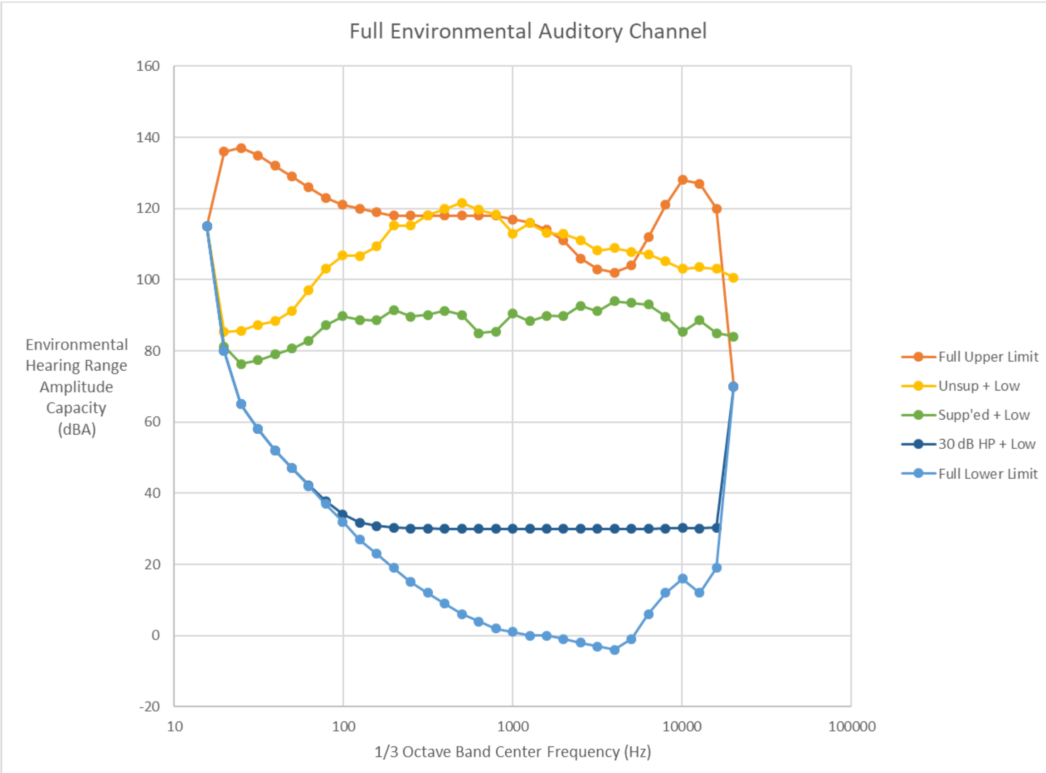

Fig. 16 Hearing threshold (full lower limit from Fig. 15) and the spectra of the suppressed and unsuppressed weapon recordings (Grasing 2013)

In addition to the unsuppressed and suppressed limits, I also have included the lower threshold limit for normal hearing plus a hearing protector offering a 30-dB attenuation at all frequencies. Each of these spectrum values is plotted combined with the normal hearing threshold from the Siemens Digital Industries Software Community Article (Mila 2019). Since the plot is in decibels, adding two incoherent sounds produces a decibel level essentially equal to the larger of the two values, except when the two values are within just a few decibels of each other.

With obscuration, the total remaining channel capacity is summed by the following expression

$$AEAC = \sum_{i=2}^{31} \frac{[Upper_i - (Lower_i + Obsure_i)]}{[Upper_i - Lower_i]} \tag{6}$$

In this expression, *Obscure* represents any noise spectrum or hearing loss spectrum that raises the threshold of auditory detectability. Applying this expression to the unsuppressed spectrum, the suppressed spectrum, and the assumed hearing protection spectrum, we find the AEAC is obscured to 5.1, 10.4, and 25.5 out of a possible 30 for the respective conditions.

We have received anecdotal reports that Soldiers often do not use attenuating hearing protection while searching for the enemy or when enemy contact might occur. This implies that the example of the 30-dB attenuating hearing protector represents an unacceptable loss of auditory environmental awareness. In a quite environment when stealth is being maintained, low amplitude sounds are critical for maintaining environmental awareness and the 30-dB hearing attenuation can easily be understood as unacceptable. While firing weapons however, low amplitude sounds cannot have such importance because they are simply not audible. During a firefight, it remains valuable to hear a shouted command, even when normal conversation, for example, talking over the phone, becomes impossible. Thus, benefits of suppressors are clearly indicated in Fig. 16.

In addition, we are using 200-ms time-weighted-average spectra. These strictly apply during the 200-ms interval around a weapon discharge. The attenuating hearing protector applies at all times. Thus, even though weapon fire may obscure more of the auditory environmental awareness channel than an attenuating hearing protector, the brief application of weapon noise may be more acceptable than the constant attenuation of the hearing protector, and the suppressed obscuration level remains measurably lower than the unsuppressed obscuration level. Particularly during a firefight, momentary reduction of the auditory environmental awareness channel may not produce the same overall Soldier reaction produced by using constantly attenuating hearing protection.

As indicated, no guidance is available giving the importance of different frequencies in supporting auditory environmental awareness. Also, no specific information is available on how different amplitude ranges might influence auditory environmental awareness. We presume the entire ranges of amplitudes and frequencies that have evolved in the mammalian ear contribute to auditory environmental awareness. Although further information could refine this analysis, we offer the previous analysis as a method of specifying human factors of suppressor performance. This evaluation method can be used to measure the allowed environmental auditory awareness provided by suppressed weapons and how their available AEAC compares with the unsuppressed weapon. Combined with Soldier feedback, desired and required levels of the AEAC can be determined to guide suppressor acquisition.

2.2.11 Auditory Hazards from Muzzle Blast Impulse

Research testing has shown that simulated combat team performance can decrease when participants use communication devices that simulate hearing loss attenuation (Sheffield et al. 2016). The result showed by Sheffield et al. (2016) can explain why Soldiers occasionally hesitate to use attenuating hearing protection when enemy contact could take place. If suppressors sufficiently reduce the auditory hazard experienced by Soldiers using suppressed weapons, Soldier hearing may be more effectively protected than with attenuating hearing protection and Soldiers will maintain higher levels of combat team performance.

Suppressors are expected to reduce the auditory hazards that Soldiers encounter from exposure to muzzle blasts. To evaluate auditory risk, we apply AHAAH described in MIL-STD-1474E (DOD 2015). AHAAH is a software analysis process that calculates the dynamic displacement of the basilar membrane in the inner ear and determines damage to hair cell cilia based on basilar membrane displacements.

The research basis of AHAAH is detailed by Price and Kalb (2018). AHAAH applies the electric-mechanical-acoustic analogies, which are originally credited to James Clerk Maxwell (Bokulich 2015). The analogies have been discussed in scientific literature since the mid-1800s and are detailed by Olson (1948). They can be understood by recognizing the oscillations of a mass on a spring, an electrical circuit, and a resonating cavity are each described by the same form of differential equation, which contains analogous driving, damping, and inertial terms.

Windows software for AHAAH is available without cost, it requires no installation, and instructions for its use are available (Fedele et al. 2013).

To illustrate the application of AHAAH, we consider recorded M110 rifle (7.62-mm) muzzle blasts measured by Grasing (2013). A suppressed and an unsuppressed muzzle blast, both measured 5 m from the muzzle, at 165° from the shot line (to the shooter's left), are shown in Fig. 17.

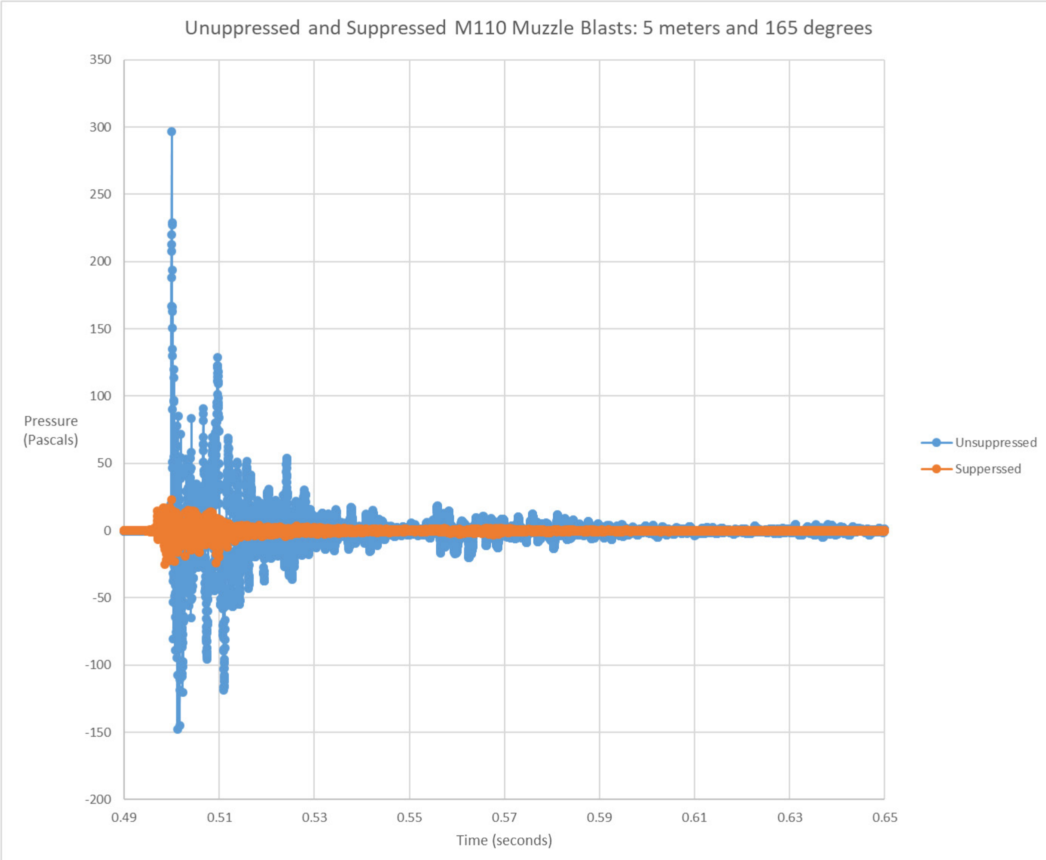

Fig. 17 Suppressed and unsuppressed muzzle blast, both measured 5 m from the muzzle, at 165° from the shot line (to the shooter's left)

The measurements shown in Fig. 17 were recorded at a rate of 65536 points per second. When input to AHAAH, the significant portions of the waveforms are selected for further analysis.

These waveforms and their 1/3 octave band levels are superimposed and displayed in the AHAAH screenshot shown in Fig. 18.

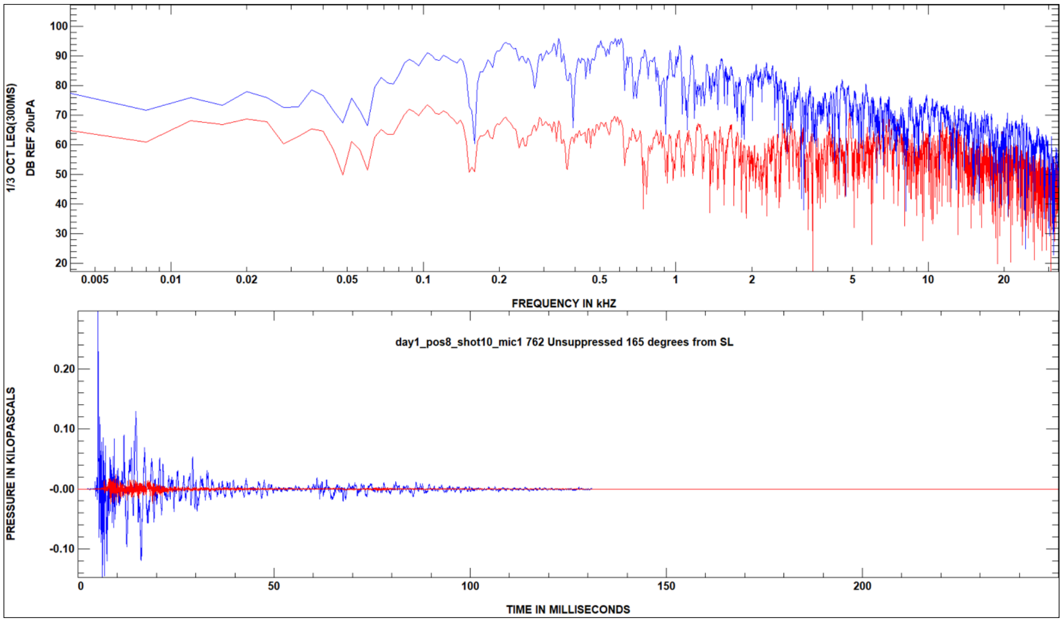

Fig. 18 AHAAH screenshot with waveforms and their 1/3 octave band levels superimposed and displayed

In the graph in Fig. 18, note the AHAAH plots pressure values in kilopascals, but AHAAH accepts input in pascals, as shown in Fig. 17.

Performing the Warned and Unwarned analysis on these waveforms gives the results shown in Table 6.

Table 6 Warned and Unwarned analysis of waveforms

Quantity Name	Unsuppressed	Suppressed
Peak Pressure (dB)	143.4	121.9
Hazard Value (Warned) (ARU)	14.4	0.37
Hazard Value (Unwarned) (ARU)	97.3	2.71
A-weighted Energy (J/M^2)	0.074	0.001
Number Allowed (Warned)	34	1340
Number Alowed (Unwarned)	5	184

While these waveforms were not measured at the shooter's ear, their application illustrates how AHAAH can be applied to assessing suppressor performance in reducing auditory hazard. AHAAH quantifies the hazard of noise exposure in auditory risk units (ARU). Price and Kalb (2018) correlated the onset threshold of permanent loss with a value of 500 ARU, which therefore is the limit for occasional exposure.

Price and Kalb (2018) indicate AHAAH is intended to apply to waveforms that mechanically damage the ear by dynamic disturbance. They indicate that AHAAH is intended to apply to waveforms with peak amplitudes above 140 dB. Thus, while the AHAAH algorithm can differentiate suppressors that keep peak pressures below 140 dB, AHAAH may not provide a precise health hazard indication when peak pressures are reduced below 140 dB.

Concurrent with the acceptance of MIL-STD-1474E, the Program Manager, Army Hearing Program, established an interim Army medical health hazard assessment criterion for impulsive noise exposure (Dye 2020). It differs from the criterion specified for the Army in MIL-STD-1474E and is based on impulsive auditory hazard assessment processes in the former MIL-STD-1474D. A description of the criterion is in the attachment titled “Robinette - 2015 - Interim APHC HHA Guidance. Clarification of the Interim APHC HHA Guidance” was given by Merkley (2020). To our knowledge, no further final criterion has replaced this interim guidance. Thus, while AHAAH may not provide a precise health hazard assessment, it specifies materiel acceptability and can provide comparative assessments between weapons, suppressed and unsuppressed.

2.2.12 Potential Influence on Marksmanship

Tactile, acoustic, and vestibular stimuli all contribute to eliciting the startle reflex (Yeomans et al. 2002). Muzzle blast is an acoustic stimulus that also contributes to an acoustic startle reflex reaction. The acoustic startle reflex has been studied by neuroscientists for several decades (Davis 1984) and studies continue. The human startle reflex is described by Brown et al. (1991). Kryter (2013) describes the human response to noise, attributing the initiation of the acoustic reflex to noises over 80 dB. Ramirez-Moreno and Sejnowski (2012) also cite acoustic reflex initiation with sounds at 80 dB and present a working model of the acoustic reflex, describing the neurological initiation and inhibition processes of the reflex. They cite reflex dependence on the physical, emotional, and cognitive states of the individual. Gamble et al. (2018) show that training influences decision processing, and therefore may influence marksmanship through the cognitive state factor.

Auditory contributions to the startle reflex are described by Kryter (2013). To influence marksmanship, the shooter must anticipate and pre-trigger the acoustic startle reflex. Brasher et al. (1969) show while firing a pistol, the acoustic startle reflex was anticipated, pre-triggered, and measured when a misfire occurred during a pistol shooting. Startle, attributed to anticipated recoil (tactile stimuli), has been shown to reduce marksmanship (Harper et al. 1996; Morelli et al. 2017). The many factors that control the startle reflex (Ramirez-Moreno and Sejnowski 2012) offer insight regarding the possible basis for marksmanship variability (Scribner 2020), which may depend on the shooter’s state of mind as well as the shooter’s physical condition.

Since the startle reflex can be initiated with many different stimuli, it is difficult to isolate the sole influence of muzzle blast on marksmanship. Tikuisis et al. (2009) showed constant noise levels up to 87 dBA did not reduce the ability of shooters to hit targets. Although they report no decrease in the shooter's ability to hit targets, they report that shooters took more time engaging targets in attempts to improve target hits, but the attempts were unsuccessful. Foss et al. (1989) found that aiming is increasingly disrupted by intermittent impulse noise at 110, 120, and 130 dB. They report a consistent and persistent disruption of steadiness during repeated aiming tasks lasting 15 s, followed by 15 s of rest. These impulsive sounds were not weapon-initiated, and while they approached muzzle blast levels, they were less than the levels we anticipate for some suppressed muzzle blasts.

No research has isolated the influence of muzzle blast on marksmanship, although anecdotal reports indicate that Soldiers shooting with suppressed weapons have improved marksmanship. Suppression of muzzle blast may improve the shooter's steadiness and result in improved marksmanship. This contradicts preliminary studies performed by Saul and Jaffe (1955) and other studies by these same authors, but they considered their studies small and preliminary. They indicate more data may show significance. The suppressor IPT is evaluating recordings of suppressed and unsuppressed small arms fire and continues to gather field data that may indicate possible reductions in startle reflex onset provided by suppressed muzzle blasts based on established understandings of impulsive sound levels known to cause discomfort. This ongoing effort will evaluate possible improvements in marksmanship that suppressors might provide.

We use MD to represent marksmanship dispersion and express MD as a function of muzzle blast A-weighted energy. A-weighted energy is the sound energy that contributes to the average person's perception of loudness. To create a hypothetical empirical model of marksmanship dispersion, MD, as a function of muzzle blast, we assume a small linear increase in MD for lower-level muzzle blasts. We apply a small slope, m, to describe increases in marksmanship dispersion as muzzle blast A-weighted energy levels, $A_{.E.}$, increase but remain low enough that the acoustic startle reaction remains small. When $A_{.E.}$ levels increase above a threshold level, A_{ET}, the rate of increase in marksmanship dispersion grows. A single parameter, G, specifies how much more rapidly MD increases after the acoustic startle reflex threshold. With dispersion data gathered for suppressed and unsuppressed muzzle blasts, we can adjust this empirical model to fit behavior, so the model can be used to describe probable marksmanship behavior as a function of muzzle blast A-weighted energy at the shooter's ear.

Our hypothetical marksmanship dispersion model, $MD(A_{.E.})$, is modeled by the following relation:

$$MD(A_E) = m\left(A_E + e^{\left(\frac{A_E - A_{ET}}{G}\right)}\right) \quad (7)$$

MD is measured in minutes of arc (MOA) and this model is illustrated in the graph in Fig. 19.

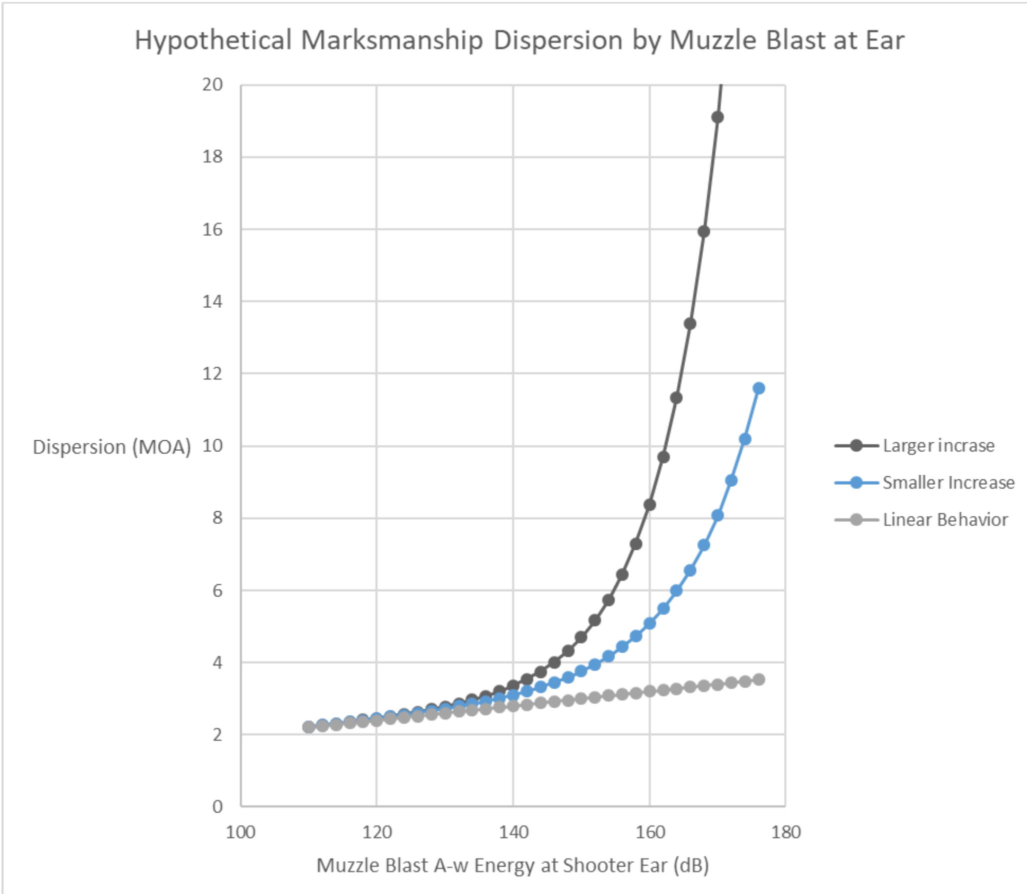

Fig. 19 Hypothetical MD(A.E.)

In this graph, the values used are the following:

$$m = 0.02\frac{MOA}{dBA}$$

$$A_{ET} = 110\ dBA$$

$$G(Larger\ Increase) = 9\ dBA$$

$$G(Smaller\ Increase) = 11\ dBA$$

As an example of this model's utility, we presume a suppressor may reduce a muzzle blast of 165 to 140 dBA at the shooter's ear. With this 25-dBA suppressor, the model would predict a dispersion of 3.3 MOA for the suppressed weapon versus a dispersion of between 12.3 and 6.3 MOA for the unsuppressed weapon, depending on how sensitive shooters are to pre-triggering the acoustic startle reaction from anticipated muzzle blasts.

We stress that whether suppressors will improve marksmanship depends on more than suppressor influence on muzzle blast level. Blowback is also a process that can contribute to activation of the startle reflex. Although toxicity may not influence startle reaction, a puff of gasses and particulates also can induce a startle reaction. Possible marksmanship improvement due to muzzle blast suppression might be offset by increased blowback. The full improvement in marksmanship that muzzle blast suppression might offer also could be obscured by using hearing protection during marksmanship evaluations with and without suppressors. Although hearing protection could reduce situation awareness, its attenuation of unsuppressed muzzle blast could make it challenging to quantify marksmanship improvements offered by muzzle blast suppression.

3. Conclusion

The metrics offered may be improved with measured data from ongoing field trials. They can be used to measure physical suppressor performance to the impact suppressors will have on Soldier operation and human perception.

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List of Symbols, Abbreviations, and Acronyms

ADM	Auditory Detection Model
$A_{.E.}$	A-weighted energy levels
AEAC	auditory environmental awareness channel
AHAAH	Auditory Hazard Assessment Algorithm for Humans
ARL	Army Research Laboratory
ARU	auditory risk unit
ATC	Aberdeen Test Center
DEVCOM	US Combat Capabilities Development Command
DOD	Department of Defense
EPA	Environmental Protection Agency
HRED	Human Research and Engineering Directorate
IPT	Integrated Process Team
MD	marksmanship dispersion
MOA	minutes of arc
NATO	North Atlantic Treaty Organization
S-AI	shouting articulation index

1 DEFENSE TECHNICAL
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TECH LIB

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1 USA NSRDEC
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NATICK MA 01760-2642

1 OSD OUSD ATL
(PDF) HPT&B B PETRO
4800 MARK CENTER DRIVE
SUITE 17E08
ALEXANDRIA VA 22350

ABERDEEN PROVING GROUND

15 DEVCOM ARL
(PDF) FCDD RLH
J LANE
Y CHEN
P FRANASZCZUK
A MARATHE
K MCDOWELL
K OIE
FCDD RLH F
J GASTON (A)
FCDD RLH FA
A DECOSTANZA
FCDD RLH FB
D BOOTHE (A)
FCDD RLH FC
K COX (A)
PD FEDELE
KF FLUITT
FCDD RLH FD
A FOOTS (A)
FCDD RLH FE
D HEADLEY
FCDD RLW WD
G OBERLIN