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TESTING PROTOCOL ON ACOUSTIC SIGNATURE MEASUREMENT OF SMALL ARMS SUPPRESSORS

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NATO LETTER OF PROMULGATION

30 August 2021

1. The enclosed Allied ENGINEERING Publication AEP-4785, Volume I, Edition B, Version 1, TESTING PROTOCOL ON ACOUSTIC SIGNATURE MEASUREMENT OF SMALL ARMS SUPPRESSORS, which has been approved by the nations in the NATO ARMY ARMAMENTS GROUP (NAAG), is promulgated herewith. The recommendation of nations to use this publication is recorded in STANREC 4785.

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CHAPTER	RECORD OF RESERVATION BY NATIONS
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RECORD OF SPECIFIC RESERVATIONS

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CHAPTER 1 INTRODUCTION

1.1. Introduction

1. The objective of this section is to provide a testing protocol to accurately measure the far-field acoustic characteristics of a suppressor. A suppressor is a device attached to or part of the barrel of a small arm, which reduces the amount of sound and visible muzzle flash generated by firing. Suppressors are typically constructed of a metal cylinder with internal structures to reduce the sound of firing by slowing the escaping propellant gas.

2. This section will describe a measurement and analysis procedure which provides relevant acoustic data for further applications.

1.2. Background

1. In order to determine the acoustic signature of a suppressed small arm, it is necessary to collect the pressure-time history at various locations. The pressure-time history captured contains the information necessary to enable the calculation of all possible metrics. Figure 1 and Figure 2 below show typical pressure-time curves containing the projectile sound (Mach wave), muzzle blast and the ground reflection of the muzzle blast for a suppressed and unsuppressed weapon.

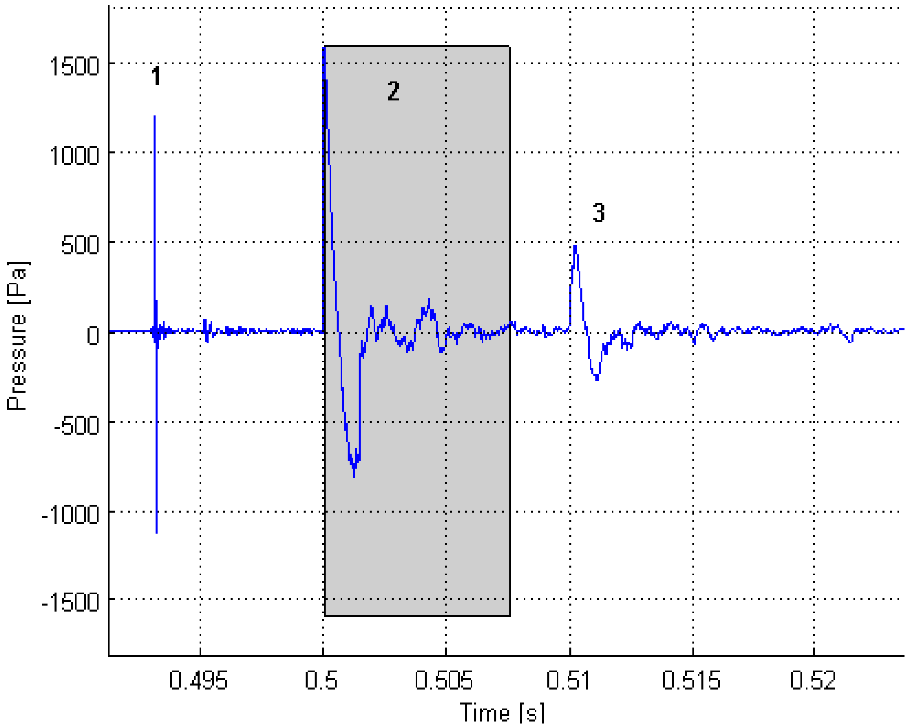

Figure 1 A pressure-time curve of an unsuppressed weapon showing 1) bullet shockwave, 2) muzzle blast and 3) muzzle blast and bullet shockwave ground reflections.

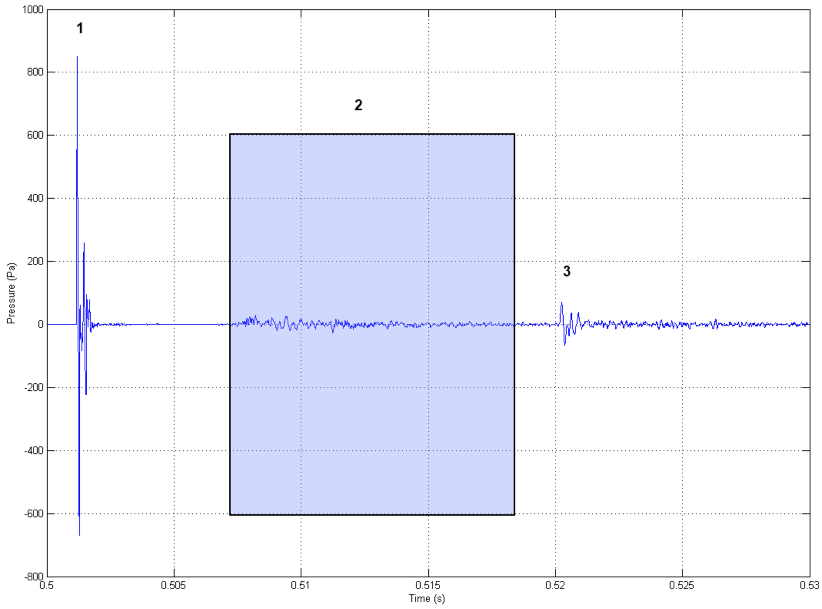

Figure 2 A pressure-time curve of a suppressed weapon showing 1) bullet shockwave, 2) muzzle blast and 3) muzzle blast and bullet shockwave ground reflections.

2. The method provided within this document will ensure a level of commonality that will allow data to be exchanged regardless of any subsequent analysis an individual nation may require.

3. Measuring the acoustic properties of a small arm system may be done for the following reasons:

a. Determine the signature; and

b. Determine the impact:

(1) Environmental impact;

(2) Command and Control (C^2); and

(3) Noise Induced Hearing Loss (NIHL).

4. To determine the metrics that describe the effect of a suppressor on signature, environmental impact and C^2, pressure-time histories measured in the far field[1] are required. The metrics necessary for those considering NIHL require additional measurements that are defined by the specific hearing damage risk criteria that are being used. Commonly, for military applications MIL-STD-1474 (Department Of

[1] Far field in this context is defined as a distance 5 m or greater from the weapon where the acoustic propagation can be assumed to approach linear.

Defense Design Criteria Standard Noise Limits) is used when NIHL is the consideration. The discussion of hearing damage-risk criteria for weapon noise is outside of the scope of this document; therefore, measurements in the near field are excluded from this testing protocol.

1.3. Scope

1. The following procedure is a balance between practicalities (‘ease of use’) and an acceptable level of error (‘completeness’).

2. The scope of this test procedure is to capture the pressure-time history from suppressed or unsuppressed small arms in the far field from which the following metrics can be determined:

   a. ⅓ Octave band Sound Exposure Level ($L_E(\alpha)$);

   b. Sound Exposure Level ($L_E(\alpha)$);

3. Both values are strongly dependent on the sound emission angle with respect to the bore axis of the weapon. How to derive these quantities mathematically is detailed in Annex A.

4. With these values you are able to determine the effects of adding a suppressor to a weapon, determine the signature of a small arm as measured in the far field and to assess the possible environmental impact from small arms firing noise.

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CHAPTER 2 TESTING PROTOCOL

2.1. Basics for Measurement Set-Up

1. An acoustic signature and the propagation of that signature, is dependent on the environmental variables and surroundings in which it is measured. This standard is designed to minimise these sources of interference and environmental variables. Following the measurement recommendations should provide pressure-time data that can be normalised from the environment using correction factors allowing application to the requirements specified within the scope of this document.

2. It is inevitable that ground reflections will occur in the measured time signal, but these can be separated from the direct signal by windowing techniques. The time difference between the direct signal and the ground reflections depend on the distance between muzzle and sensor and the height above ground. In the production of this document it was found that for the majority of small arms, 95% of the energy of the direct blast signal were contained within a 12.5 ms time window. On this basis, an arena that provides a 12.5 ms delay between the arrival of the blast signal and the ground reflection is specified. To achieve this delay, both the small arm and sensors are to be elevated to a minimum of 4 m from the ground, and a horizontal separation distance of 5 m between the muzzle and all sensor positions must be used.

3. The measurement set-up detailed below is only applicable if the un-weighted peak pressures at the sensor positions do not exceed 3.2 kPa[2]. Measurements must be conducted outdoors.

   a Firing Platform: A firing platform is required to elevate and support the weapon support. Care must be taken to minimise the presented area of the mounting platform (including the floor underneath the weapon support) as much as practically possible to minimize unwanted reflections. Utilization of open framed structures such as scaffolding should be used to elevate the platform (example shown in Figure 3).

[2] The maximum un-weighted peak pressure at the sensor location was raised from 1 kPa (as commonly referenced in documents such as ISO 17201) to 3.2 kPa, because the sensor position is 5 m from the muzzle in this instance. The maximum un-weighted peak pressure limited to 3.2 kPa (164 dB) will allow a wider range of sensors to be used.

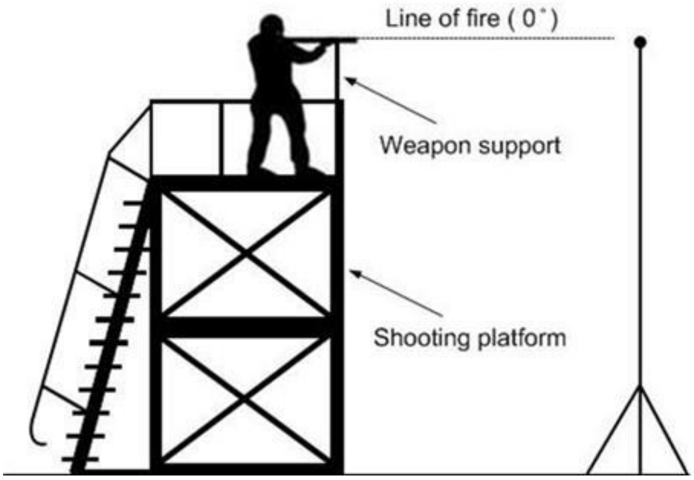
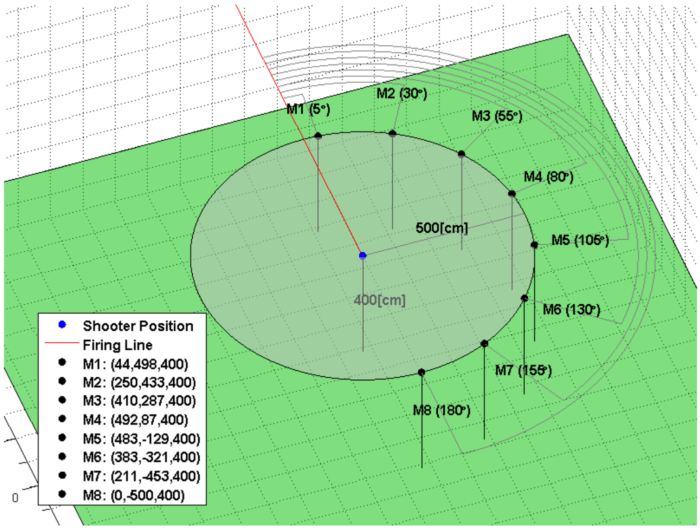


Figure 3 Example of possible firing platform.

b. Weapon support: A weapon support is needed to ensure that a consistent shooting position can be maintained shot-to-shot to the defined tolerances. The weapon must be supported via a means that minimises the possibility of reflection from the mount. The weapon must be fired by a standing shooter.

c. Sensor mount: The frequency response of a sensor is dependent on the orientation of the sensor with respect to the incoming sound wave, especially for higher frequencies. The sensor should be oriented to produce as flat a frequency response as possible. It is important to design a mounting array with no reflective obstructions around the sensor. Any structures that may introduce an acoustic reflection (walls, mounts etc.) must be 5 m or further beyond the sensor to ensure that no reflections are measured within 12.5 ms of the onset of the direct signal.

d. Weapon position: The weapon must be placed so that either the end of the muzzle or the end of the suppressor is at the centre of the arena as shown in Figure 4 as shooting position.



Microphone number	Angle [deg]	X [cm]	Y [cm]	Z [cm]
M1	5	44	498	400
M2	30	250	433	400
M3	55	410	287	400
M4	80	492	87	400
M5	105	483	-129	400
M6	130	383	-321	400
M7	155	211	-453	400
M8	180	0	-500	400

Figure 4 Example Transducer placement specification.

e. Sensor positions: The measurement set-up requires measurements in at least 8 positions at a radius of at least 5 m from the muzzle. Sensors will be placed in a semi-circle with the 1st sensor about the shot line for example 5° off shot line and the remaining sensors placed at angular increments as in the example shown in Figure 4. Sensors must be placed so that the sensing surface is ±0.1 m from the height of the bore axis [3] (see Figure 5) whilst not being below the minimum distance.

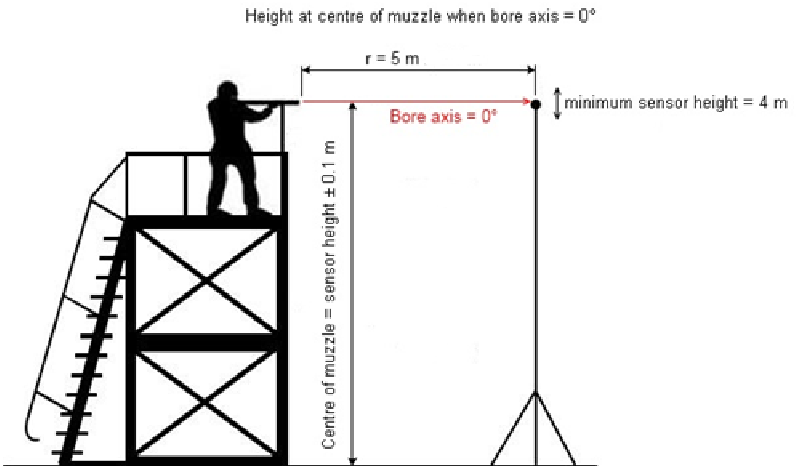


Figure 5 Example platform showing weapon position and minimum ± 0.1 m tolerances.

[3] The bore axis is the angle of the line for fire taken from the centre of the muzzle of a weapon to the point of impact on a target assuming the bullet travels in a straight line.

f. Avoiding shockwave overlap: Interference between the muzzle blast shockwave[4] and bullet shockwave[5] (Figure 6) will produce too high pressure measurements if a microphone is placed in the areas where they intersect.

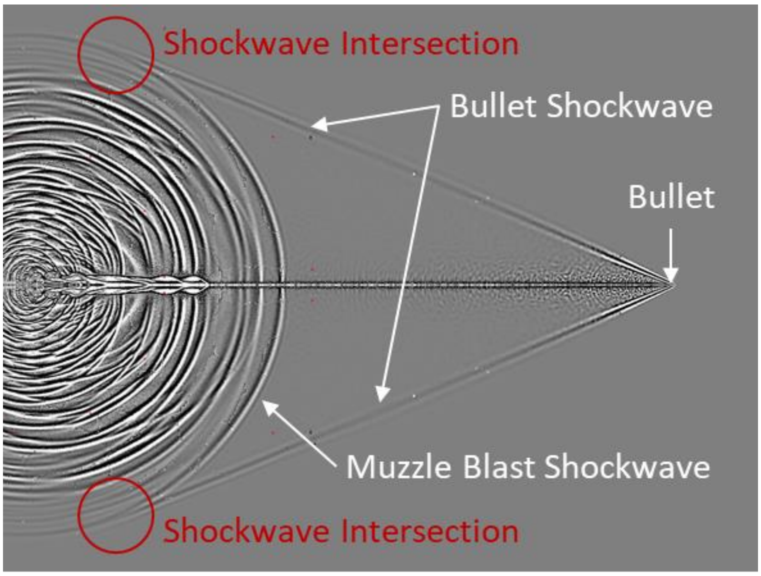


Figure 6 Schlieren image showing the intersection of the bullet and muzzle blast shockwaves.

The angle at which this intersection occurs relative to the line of fire and the muzzle (ε_0) can be closely approximated[6] by calculating the arccos of the ratio of the speed of sound (c) to the velocity of the bullet (v_b), as is illustrated in Figure 7. For measurements taken close to this angle, it will be very difficult to separate the muzzle blast from the bullet shockwave, potentially resulting in overestimation of the muzzle blast during analysis.

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[4] When a bullet exits the barrel of a weapon, a spherical shockwave, typically referred to as "muzzle blast" is generated by the rapid release of pressurized propellant gasses.

[5] When a bullet travels with supersonic speeds, it creates a shockwave at a well-defined angle relative to the path of the bullet. This bullet shockwave only occurs in front of the muzzle since it propagates from the path of the bullet.

[6] This is an approximation as ε_0 depends on the bullet velocity, which decreases over time. However, given the microphone distance is only 5 m from the muzzle, the bullet velocity may be assumed to be constant. Factors such as a muzzle device may also have some influence on ε_0.

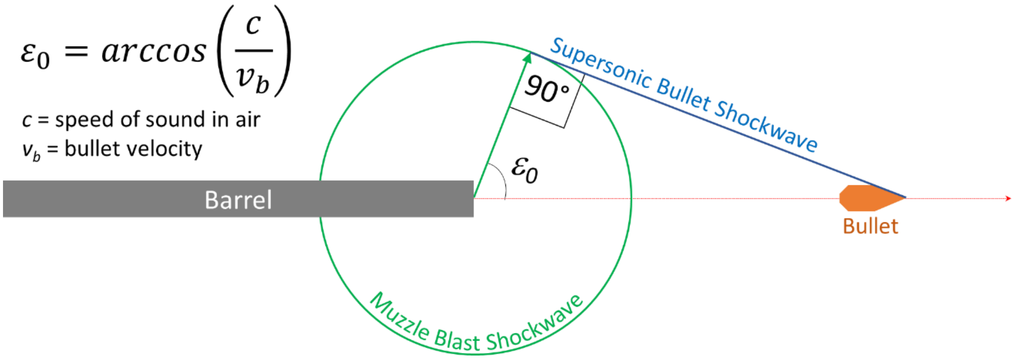

Figure 7 The angle relative to the muzzle and the line of fire at which muzzle blast and supersonic bullet shockwaves intersect (ε_0) is dependent on the bullet velocity (v_b) and the speed of sound (c).

It is therefore important to calculate ε_0 and ensure that the sensor position is either less than or greater than that angle[7]. If the angle of the sensor position is greater than ε_0, the projectile shockwave will not be observable, thus the muzzle blast will already be effectively isolated without any further need for windowing. If the angle of the sensor position is less than ε_0, the bullet shockwave will arrive at the sensor before the muzzle blast. The time separation between these two will increase as the sensor angle is decreased relative to ε_0. Typically the sensor angle should be at least 5 to 10 degrees less than ε_0, but this depends on the projectile speed. Choosing the sensor angle to be much smaller than ε_0 makes data analysis easier, but may lead to lack of data at angles between the sensors at each side of ε_0. As a rough guideline, for bullet speeds of common military rifles in caliber 5.56 x 45 mm and 7. 62 x 51 mm, with standard ammunition, the sensor angle should not be between 45 and 70 degrees.

g. All sensors shall be positioned within ±0.1 m of a plane containing the bore axis whilst not going below the minimum sensor height of at least 4 m above the ground. As such, when a bore axis has an incline, the height of the sensors around the hemisphere (sensor plane) must remain within ±0.1 m of the height of the bore axis with the lowest sensor being no less than 4 m from the ground (see Figure 8). Alternate sensor positions may be used when required as long as proper mathematical considerations are made in subsequent calculations.

[7] For example, if the bullet velocity is 830 m/s then ε_0 will be 65.6°, thus 70° is a good sensor position.

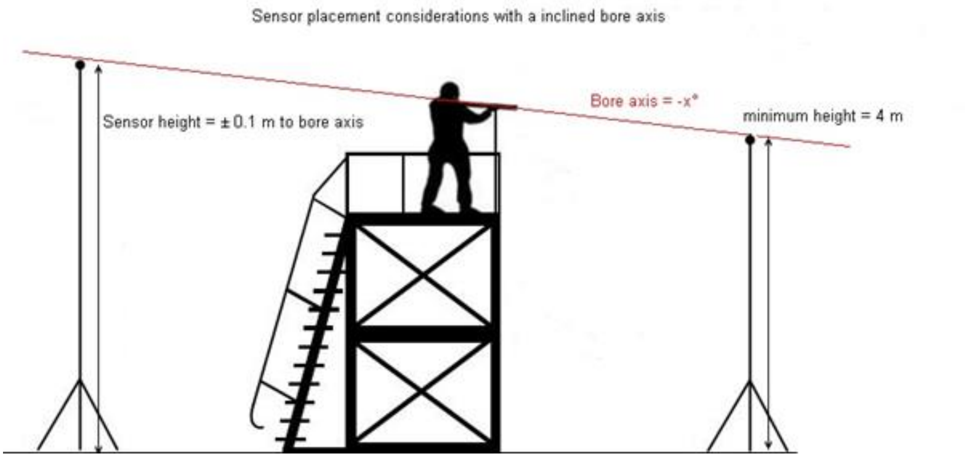

Figure 8 Diagram showing an example of the sensor offset with an inclined bore axis.

h. After placement and calibration of the sensors, before each measurement series, the sensor positions must be measured. The position of the sensor relative to the bore axis must be known to an accuracy of ±1 cm. This usually requires the use of a Total Station Theodolite, but other devices that have the required accuracy could be used.

i. The semi-circle sensor configuration assumes axial symmetry. If the configuration of the weapon, muzzle brake or suppressor indicates asymmetry, additional sensors may be required.

4. There are no restrictions for additional measurements or additional sensor positions as long as the conditions detailed above are maintained.

2.2. Environmental Data

1. The following parameters must be recorded and made available along with the pressure-time history for each firing at the same time as when the firing event was acquired:

a. Date stamp: dd/mm/yyyy;

b. Time stamp hh:mm:ss;

c. Ambient temperature at 4 m height;

d. Wind speed at 4 m height as an average over each measurement series (within the maximum allowable limit);

e. Wind direction relative to the axis of the bore; and

f. Relative humidity (within the maximum allowable limit).

2. Ambient air pressure or altitude must be reported along with the pressure-time history for each firing. One pressure/altitude measurement may be made at the beginning of a measurement series and applied to all measurements within that series.

2.3. Instrumentation

1. The equipment must have a current calibration that confirms the accuracy and precision of the required measurements.

2. The requirements for the instrumentation used in the measurement chain (transducer – amplifier – signal processing) are as follows:

a. Upper limit of the dynamic range is 164 dB or higher (about 3.2 kPa);

b. Minimum of 90 dB dynamic range:

(1) The dynamic range of the AD-converter must satisfy the requirement for the sampling rate and gain setting to be used during the measurements.

c. Minimum frequency range or bandwidth: 10 Hz – 20 kHz:

(1) The frequency response for the bandwidth must be flat within 3 dB;

(2) The stated flat frequency response must relate to the transducer orientation used during the measurements; and

(3) Alternatively, if the transducer is oriented in a direction so that the frequency response is not flat, one must correct this using frequency response data valid for that orientation, usually provided by the manufacturer.

3. Explanatory notes on the requirements:

a. For transducers close to the line of fire, a high pressure shockwave generated by a supersonic bullet will be captured by the transducer. In order to prevent the recorded signal from being clipped, the dynamic range of the transducer needs to have a minimum upper value of 164 dB.

b. A minimum dynamic range of 90 dB has been set to capture the energy in all one-third octave bands, especially for the lower frequency bands.

c. The minimum sampling rate is about 2.5 times the upper value of the frequency range of interest; e.g. 50,000 samples/second for a 20 kHz upper range. The minimum sampling rate and instrumentation specification is not intended to be used for systems designed for measurement of peak pressure[8].

4. The purpose of the prescribed instrumentation is to measure pressure-time history to be able to calculate energy based indicators, such as sound exposure level.

2.4. Best Practice During Measurement Procedure, Data Analysis And Post Processing

1. The following points provide methods and recommendations that will ensure repeatable and optimum measurements are achieved during a measurement series:

a. Calibration: Prior to the beginning of any test plan, sensors and the associated measurement chain must be verified in situ using a calibrated source of a known frequency and level. This shall be done on each microphone. Calibration should be repeated at the conclusion of a test day, after any prolonged pause (e.g. lunch break) or if there are any significant changes to the measurement arena (e.g. a microphone replacement, or when power is turned back on after being off).

b. Adverse environmental parameters: It is recommended that measurements are not taken if the wind speed at the sensor height is greater than 2.24 m/s (5 mph), or if there is a continuous spell of rainfall.

c. Sensor protection: A microphone exposed to wind or to any operational air flow with velocity exceeding 1.56 m/s (3.5 mph) may be equipped with a windscreen recommended by the sensor manufacturer, provided that the frequency response of the system can be maintained within the requirements of this document.

d. Sample size: It is expected that at a distance of 5 m from the weapon the (broad band) Sound Exposure Level (L_E) will not vary more than 1 dB for an unsuppressed weapon and 2 dB for a suppressed weapon. The first shot may behave differently to that of the subsequent shots. This must be recorded but not included within the statistical average. For these small variations, it will be sufficient to perform at least 10 measurements

[8] If the bandwidth of interest is higher than 20kHz then the minimum sampling rate should be increased accordingly

for every microphone position to determine the average L_E. If larger deviations occur, more shots should be measured. The sample size (N) should be such that the standard deviation of the average (σ_{avg}) should be less than 0.5 dB. The standard deviation of the average is related to the standard deviation of the sample (σ) as shown in Annex A.

e. Correction factors: The application of correction factors to the raw pressure-time curves shall be recorded and saved with the noise data files. The correction factors include, but are not limited to, system gain corrections, system frequency response corrections and microphone/transducer directivity corrections.

f. DC bias removal: The DC offset of the time signal should be removed before further analysis. An estimate of this offset can be obtained as the average value over the samples before the onset of the first impulse (bullet shock wave or muzzle blast).

g. Selecting the 12.5 ms window: To ensure that the shockwave (and ground reflections) are not included in the selected window, the onset of the muzzle blasts is usually manually determined. The arrival of the muzzle blast is more obvious with an unsuppressed weapon than with a suppressed weapon as such there is some degree of subjectivity when determining the onset of the muzzle blast with a suppressed weapon. In order to reduce this subjectivity, a window that ensures the maximum Sound Exposure Level is determined before the arrival of the ground reflection should be used. The formula required to calculate the Sound Exposure Level (L_E) is shown in Annex A.

h. Calculating the Sound Exposure Level (L_E) in ⅓ Octave bands to base 10: The ⅓ Octave bands should be generated so that they are in accordance with Table 1 in Annex A. The amount of zero padding required will then be a function of the lowest frequency required, the sampling rate and the windowing technique. The formulae required to calculate the Sound Exposure Level (L_E) in ⅓ Octave bands to base 10 are shown in Annex A.

2. A background in signal analysis is required for the data analysis; e.g. when applying a rectangular window, offset removal and zero padding.

3. Interpretation of data after collection (such as statistical analysis techniques and various weighting options) is outside the scope of this document.

2.5. Data Report

1. In order to understand fully the conditions under which the acoustic measurement was taken, it is necessary to record and make available the following information:

a. Configuration: weapon name, barrel length, caliber, suppressor type and specification of the ammunition (name, type, propellant mass, mass of the bullet);

b. Measurement Chain: transducer name, model and location, cable type/s, amplifier name and model, data recorder name and model;

c. Calibration Tone: type or model used;

d. Ambient air pressure or altitude;

e. For each shot:

(1) Shot Date Time: Date stamp (dd/mm/yyyy) and Time stamp (hh:mm:ss);

(2) Environmental conditions: Ambient temperature, wind speed and direction relative to the axis of the Bore and relative Humidity. The measurement height should also be specified;

(3) For each transducer location:

i. Primary data: Sound Exposure Level (L_E) in ⅓ Octave bands to base 10 and Sound Exposure Level (L_E) for each microphone position for each shoot (see Annex A); and

ii. Correction factors: system gain corrections, system frequency response corrections and microphone/transducer directivity corrections.

f. Graphs of the Sound Exposure Level as a function of angle. Examples of graphs are given in the Annex A.

2.6. Definitions

See Annex A.

ANNEX A DEFINITIONS

A.1. Continuous Regime

Instantaneous Pressure

$$p(t)$$

Event Duration

$$T$$

Peak Sound Pressure

$$p_{peak}$$

Sound Exposure

$$E = \int_T p^2(t)dt$$

Sound Exposure Level (L_E)

$$L_E = 10log\left(\frac{E}{E_0}\right)$$

$$E_0 = 400x10^{-12}Pa^2\ s$$

Peak Sound Pressure Level (L_{peak})

$$L_{peak} = 10log\left(\frac{p_{peak}^2}{p_{ref}^2}\right)$$

$$p_{ref} = 20\mu Pa$$

The standard deviation of the average

$$\sigma_{avg} = \sigma/\sqrt{N-1}$$

A.2. Discrete Regime

Basic Definitions

f_s	Sampling frequency
f_{Nyq}	Nyquist rate
f_{max}	Maximum frequency in signal
N	Number of data points included in the analysis
T	Time period analyzed

$$f_{Nyq} \geq a f_{max}$$

The value of "*a*" is directly related to the role off characteristics of the analogue filter. The minimum value of *"a"* is 2. In practice values over 3 are often used.

$$f_s \geq f_{Nyq}$$

Derived Definitions

$$\Delta f = \frac{f_s}{N}$$

$$N = T f_s$$

$$\Delta f = \frac{1}{T}$$

$$\Delta t = \frac{1}{f_s}$$

Instantaneous Pressure

$$p_i$$

DFT Frequency Component

$$P_i = Re + jIm$$

$$j = \sqrt{-1}$$

$$|P_i| = \sqrt{Re^2 + Im^2}$$

Parseval's Theorem

$$\sum_{i=0}^{N-1} p_i^2 = \frac{\sum_{i=0}^{N-1} |P_i|^2}{N}$$

Sound Exposure

$$E = \Delta t \sum_{i=0}^{N-1} p_i^2 = \frac{\Delta t}{N} \sum_{i=0}^{N-1} |P_i|^2$$

Sound Exposure Level (*L*L_E)

$$L_E = 10log\left(\Delta t \frac{\sum_{i=0}^{N-1} p_i^2}{p_{ref}^2}\right) = 10log\left(\frac{\Delta t}{N} \frac{\sum_{i=0}^{N-1} |P_i|^2}{p_{ref}^2}\right)$$

Relationships between Two-Sided and One Sided FFT

For a time based pressure signal defined as,

$$p(t) = A_0 + \sum_{j=1}^{K} A_j sin(2\pi f_j t)$$

A two-sided power spectrum is defined as *D(j)* and a single-sided power spectrum as *S(j)*. The length of the two-sided power spectrum is given as N. The following rule applies for conversion of a two-sided power spectrum to a single one.

$$S(j) = D(j), \qquad for\ j = 0$$

$$S(j) = 2D(j), \qquad for\ j = 1\ to\ \frac{N}{2} - 1$$

$$A_0 = \frac{|S_0|^2}{N^2} = \frac{|D_0|^2}{N^2}$$

$$\frac{{A_j}^2}{2} = \frac{|S_j|^2}{N^2} = 2\frac{|D_j|^2}{N^2}, \qquad j = 1\ to\ \frac{N}{2} - 1$$

A.3. One-Third Octave Analysis

The One-Third Octave Frequency Bands are defined in accordance with "ANSI S1.11-2004: specification for octave-band and fractional-octave-band analog and digital filters" and "ISO 266: preferred frequencies".

Exact middle Frequency

$$f_m = 10\hat{}\frac{n}{10} f_r$$

where $f_r = 1000\ \mathrm{Hz}$, and n is an integer, positive or negative.

Lower Frequency Bound

$$f_1 = 10^{-1/20} f_m$$

Upper Frequency Bound

$$f_2 = 10^{1/20} f_m$$

In the table of one-third octave frequency bands, the series of frequencies may be extended indefinitely in either direction by successive multiplication or division by powers of ten.

Middle Frequency		Lower Frequency	Upper Frequency
Reported (Hz)	Exact (Hz)	(Hz)	(Hz)
25	25.119	22.387	28.184
31.5	31.623	28.184	35.481
40	39.811	35.481	44.668
50	50.119	44.668	56.234
63	63.096	56.234	70.795
80	79.433	70.795	89.125
100	100.00	89.125	112.2
125	125.89	112.2	141.25
160	158.49	141.25	177.83
200	199.53	177.83	223.87
250	251.19	223.87	281.84
315	316.23	281.84	354.81
400	398.11	354.81	446.68

500	501.19	446.68	562.34
630	630.96	562.34	707.95
800	794.33	707.95	891.25
1000	1000.0	891.25	1122.0
1250	1258.9	1122.0	1412.5
1600	1584.9	1412.5	1778.3
2000	1995.3	1778.3	2238.7
2500	2511.9	2238.7	2818.4
3150	3162.3	2818.4	3548.1
4000	3981.1	3548.1	4466.8
5000	5011.9	4466.8	5623.4
6300	6309.6	5623.4	7079.5
8000	7943.3	7079.5	8912.5
10000	10000	8912.5	11220
12500	12589	11220	14125
16000	15849	14125	17783
20000	19953	17783	22387

Table 1 One-Third Octave Frequency Bands.

Spectral Analysis of Waveforms

Sound Exposure Level (L_E) without A Weighting

The Sound Exposure Level for a frequency band with a lower frequency bound of f_1 and an upper frequency bound of f_2 is,

$$L_{E_{f_1-f_2}} = 10log\left(\frac{2\Delta t}{N}\frac{\sum_{i=f_1}^{f_2}|P_i|^2}{p_{ref}^2}\right)$$

The factor of *2* in the above equation is based on $|P_i|$ being from a two-sided FFT algorithm. It is valid as long as the DC component, 0 Hz, is not included in the analysis.

A.4. Graphs of the Sound Exposure Level

For an overview of the results it is recommended to give graphs of the angle dependent Sound Exposure Level L_E as determined at the different sensor positions. In the following two graphs examples have been given: First the angle dependent results are shown for the (broad band) L_E for a suppressed weapon as an average over 20 shots. Such plots often exhibit a decline in levels from angle 0 deg to 180 deg. Plots with different trends are often either a result of a distinctly directive muzzle device (e.g. Barrett M82) or by placement of a sensor in a position where arrival of both the bullet shockwave and the muzzle blast are coincident in time.

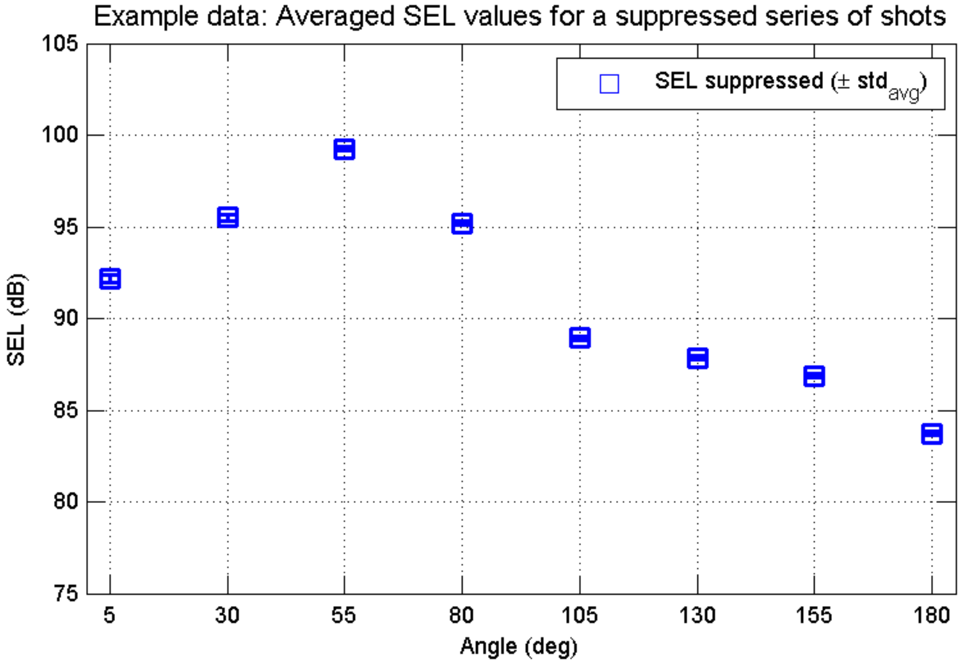

Figure A.1. Averaged SEL values for a suppressed series of shots as a function of the angle (for 8 microphones). Error bars are also given (± the standard deviation of the average based on 20 shots).

In the next figure the angle dependent results are shown for L_E for different 1/3 octave bands averaged over one series.

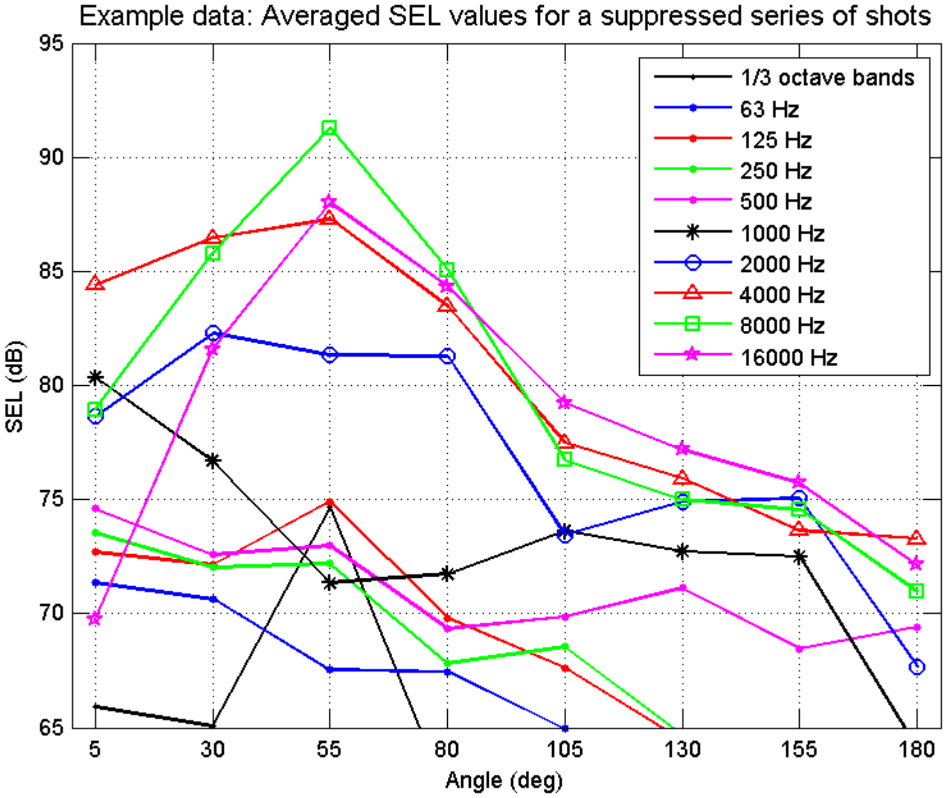

Figure A.2.A selection of averaged 1/3 octave band SEL values for a suppressed series of shots as a function of the angle.

AEP-4785 VOLI (B)(1)