OUTDOOR PROPAGATION OF IMPULSIVE SOUND

Frits van der Eerden[1], Ad van Heijningen[1]

[1] *TNO - Defense, Safety & Security, The Hague, The Netherlands,*

This contribution has been accepted based on the submitted abstract. The submitted manuscript was not reviewed and is reproduced here without edits or corrections by the conference board. Neither the EAA nor the AAA take responsibility for its contents.

Preliminary document

Abstract

The impulsive sound of large caliber weapons or explosions can travel over long distances. To calculate the sound levels at some distance from the source, a linear propagation model and therefore a linear acoustic source strength is used, in general. Nonlinear propagation effects for the shock wave, relatively close to the source, are not taken into account. By measuring the source strength at a larger distance, typically 100 to 200 meters the linear acoustic source strength can be determined.

A new method to determine the linear acoustic source strength has been developed, based on using closer measurements. At shorter distances, typically 50 meters or less from the source, deploying microphones around the weapon is simpler and faster. Also, less space is required for the measurement setup.

In a validation setup, sound measurements were carried out at two distances from a large caliber weapon: at 150 and at 50 meters. At 50 meters nonlinear effects can be observed; i.e. a faster than linear decrease of the peak sound pressure over distance and a broadening of the shockwave in time resulting in a frequency shift of the corresponding spectrum. An analytical nonlinear model is used which allows to estimate the shock wave in the time domain at various distances.

Keywords: *impulsive sound, source measurement, ground effect, nonlinear propagation*

1. Introduction

A new method is described and tested to determine the acoustic source strength for the muzzle blast or detonation from large caliber weapons based on relatively close-by measurements. At shorter distances (typically 50 meters from the source), deploying microphones around the weapon is simpler and faster. Furthermore, less space is required for the test, making the choice of a location more flexible. Due to the shorter distance, the nonlinear propagation of the shock wave towards longer distances must be taken into account. At longer distances (typically 100 to 200 meters), the nonlinear propagation is negligible, and the linear source strength can be determined at that distance. A linear acoustic source strength is included in the acoustics source database and is used for calculating sound levels around military training areas.

Figure 1. Measuring the source strength of a 155 mm muzzle blast.

The new method corrects the source strength, determined at short distances, for the nonlinear effect of propagation to longer distances. This correction is determined in the frequency domain, in octave or one-third octave bands. An analytical model is used which allows for the determination of a shock wave at various distances in the time domain and takes into account nonlinear sound propagation (which causes the shock wave to widen at larger distances).

In addition, special attention is paid to the influence of the ground, as this can yield several dB corrections for the various octave bands when determining the sound source strength. By considering the ground interference in the measurements, a more accurate estimate of the ground absorption parameter is obtained. As a result the necessary corrections for the acoustic source strength are more accurate.

The results of using the new method are compared with

Corresponding author*: frits.vandereerden@tno.nl*
Copyright: *©2026 Frits van der Eerden et al. This is an open-access article distributed under the terms of the Creative Commons Attribution 3.0 Unported License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.*

those of the existing method (NIELS[1]: Method III [1]) and it was shown that the source strength spectra agree well for the different charge sizes of a Pantserhouwitser 155 mm (charge sizes 3, 5 and 6), see Figure 1.

2. Source strength method

Figure 2 schematically illustrates how peak pressure varies with distance. Beyond the distance where non-linear sound propagation can be neglected, the pressure decreases according to the 1/R law (where R is the distance). From that point, a linear back-calculation to the source is performed, allowing this linear source strength to be used in standard models for calculating noise contours. A similar principle applies to the source strength spectrum; beyond a certain distance, the spectrum no longer changes due to nonlinear effects, such as shock wave broadening.

If measurements are taken at a shorter distance, the changes in the shock wave caused by nonlinear effects must be taken into account. This can be done using the analytical ANX model described in section 4.

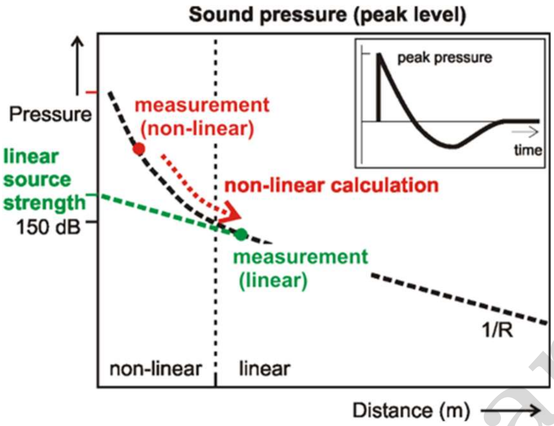

Figure 2. Schematic representation of the pressure decaying with distance, for the nonlinear and linear regime.

The shock wave at distance R_{nonlin} (e.g. at 50 meters or at the red marker in Figure 2) changes into a shock wave at a larger distance, R_{lin}. The source spectrum can be determined for both shock waves (by back-calculating linearly to the source). The difference between the two spectra results from nonlinear propagation and can be used to correct the source spectra derived from near-field measurements.

The degree of nonlinearity depends on the sound intensity. Therefore, the sound exposure level (SEL) of a Friedlander shock wave at distance R_{nonlin} is matched to the SEL measured at that same distance. The energy E for the Friedlander shock wave, in a specific direction around the weapon, is subsequently used with the ANX model at larger distances (in this case, 150 meters) to determine the Friedlander shock wave where nonlinear effects can be neglected.

3. Measurements

The measurement setup is shown in Figure 3. It involves measuring the muzzle blast using seven microphones arranged in a semi-circle. The MoD conducted measurements at the distance used for source characterization for the current method, in this case 150 meters distance (determined based on the largest charge size). TNO carried out measurements at a distance of 50 meters according to the new method. Figure 3 shows a schematic of the setup, with microphones positioned on the right-hand side, as the wind was coming from the opposite direction.

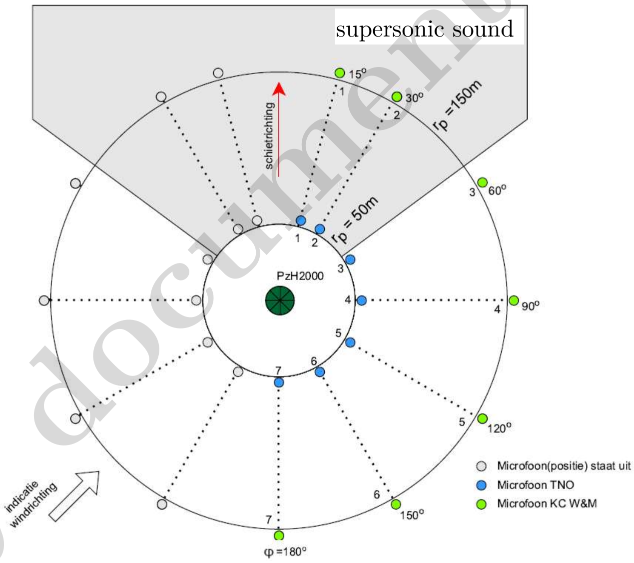

Figure 3. Measurement set-up around the 155 mm muzzle blast, using microphones at 50 and 150 meters distance.

The source method traces the measured sound back to the source by performing a PE calculation. This requires a sound speed profile (based on wind and temperature measurements at various heights) and a ground absorption value (based on ground impedance measurements).

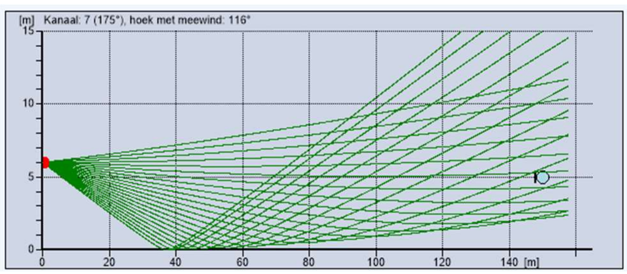

Figure 4. Sound rays for the microphone position with a moderate headwind condition.

[1] NIELS = Noise Emission Measurement Analysis; TNO-software to process acoustic measurements and to determine the source strength for muzzle blasts and detonations [1].

Preliminary document

For microphone 7 (at an angle of 175° relative to the direction of fire), there is a moderate 'headwind' condition, as the effective speed of sound in that direction decreases with altitude. The sound rays refract upwards, creating a sound shadow; however, the microphone, located 150 meters away at a height of 5 meters, is not within this shadow, making the measurements usable, see Figure 4.

The variability for the ground correction is shown in Figure 5 using each shot separately (see the results around the 0 dB line, indicated on the right). For each shot, the ground correction is calculated based on the meteorological conditions at the time of the shot (using a 5-minute average). This reveals a scatter in the results, particularly for frequencies above 500 Hz, as shown within the blue ellipse.

The source spectrum was also determined for each shot, and the same scatter is evident, as the ground correction is applied. The spectra of the measurements did not show this scatter for the frequencies above 500 Hz (as a result of turbulence), so the ground correction above 500 Hz is set to a minimum of 0 dB.

Also visible is some variation between 63 and 250 Hz, shown within the green ellipse. This stems directly from the measurements, given that the ground correction shows no variation at these frequencies.

The flow resistivity σ used for the ground impedance model has been tuned to the ground dip observed in the measurements: here located just below 125 Hz, using σ=100 kNsm^{-4}.

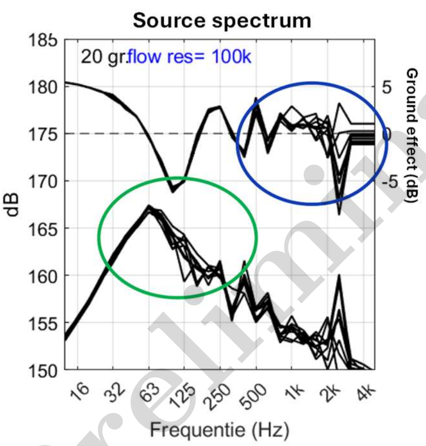

Figure 5. Source strength (lower lines) and ground correction (upper lines) for each shot, using the microphone at 20 degrees.

4. Analytical model

The model for nonlinear propagation is described in the 2024 JASA paper [3], which details the ANX model. Figures 6 and 7 illustrate this with excerpts from the paper: the Friedlander blast wave and the corresponding equations to determine the peak pressure and the positive phase duration T as a function of the explosive mass (energy E) at the distance r.

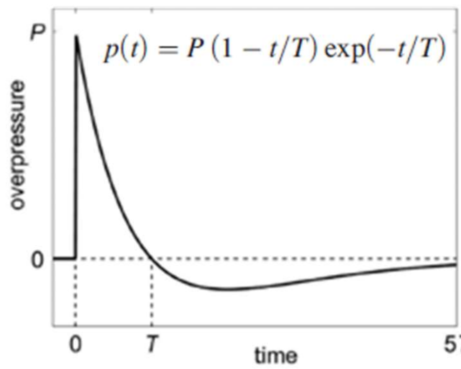

Figure 6. Friedlander waveform with shock overpressure P and positive phase duration T, copied from [3].

$$P(r) = K\rho c^2 \frac{r_*}{r}\left(\ln\frac{r}{r_*}\right)^{-1/2},$$

$$T(r) = K\beta \frac{r_*}{c}\left(\ln\frac{r}{r_*}\right)^{1/2}$$

with $\beta = 1.2,\ K = 0.38,$ and $r_* = 0.70\left(E/\rho c^2\right)^{1/3}$

Figure 7. The ANX model [3] to determine the Friedlander shockwave as a function of the explosive energy E and the distance r. The values K=0.38 and r^*= 0.70(…) are based on numerical CFD calculations.

The energy E is estimated by matching it to the measured sound exposure levels (SEL) at 50 meters distance (see the green lines and data in Figures 8 and 9). This energy is also used to calculated the Friedlander waveform at a larger distance of 150 meters. Both spectra are determined and the difference is applied as a nonlinear correction to obtain the linear source strength measured at 50 meters distance (without using a ground effect).

5. Results

The source spectra using the Friedlander waveforms at the two distances R_{nonlin} and R_{lin} are shown for charge sizes 3W and 5W in Figures 8 and 9, using the green lines. The upper green line (above 63 Hz) is based on a distance of 50 meters, while the lower one is based on 150 meters. The difference between the two lines represents the nonlinear correction. Since the spectrum at 50 meters is above the one for 150 meters, the nonlinear source level will be higher, so the difference relative to the 150 meter measurement must be subtracted from the source level when the 50 meter distance is used.

The reverse applies to frequencies below 32 Hz (though this is less visible in the figures): here, the correction actually increases the source level. This aligns with the observation that the shock wave broadens with increasing distance due to nonlinear effects, causing acoustic energy to shift from higher to lower frequencies. This phenomenon can be quantified using the ANX model.

Preliminary document

The measured source levels are also plotted in Figures 8 and 9, shown with the blue lines. It shows that the source level derived from the 50 meter distance yields higher values at high frequencies compared to the source level derived from the 150-meter distance, as expected.

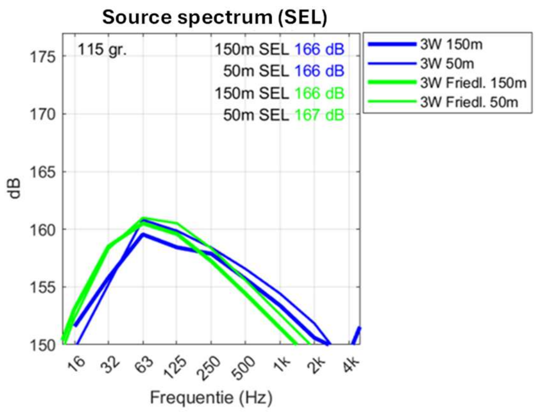

Figure 8. Blue lines: source spectrum for a 3W charge size using distances of 150 and 50 meters, including ground and meteorological corrections. Green lines: source strength based on Friedlander shockwave, without ground correction. The Friedlander SEL source level at 50 meters is matched to the measurements (upper green line).

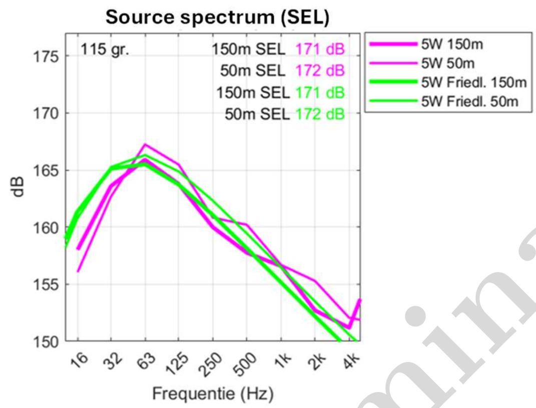

Figure 9. As Figure 8, for a 5W charge size.

Note that the spectrum of the Friedlander shock wave follows the shape of the measured source spectrum. The Friedlander shock wave apparently contains more low-frequency energy compared to the measurements. This is expected to have a negligible effect on the nonlinear correction as this correction does not need to account for this specific spectral discrepancy relative to the measurements.

The source strengths for charges sizes 3W and 5W are also shown in Figures 10 and 11. The thick dashed line represents the source strength based on the 150-meter measurements (the reference), while the thick solid line represents the source strength based on the 50-meter measurements, corrected for nonlinear propagation from 50 to 150 meters.

For completeness, the dotted line also shows the source strength derived from the 50 meter measurements, without the nonlinear correction, as well as the source strength recorded some years earlier (Database).

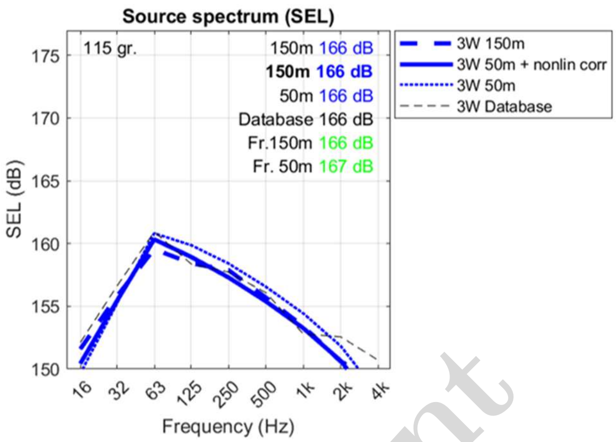

Figure 10. Source strength for charge size 3W, using 150 meters distance (the reference) and 50 meters distance (nonlinear corrected).

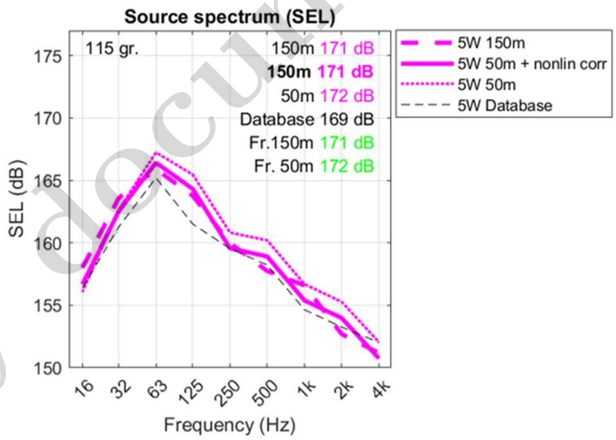

Figure 11. As Figure 10, for a 5W charge size.

The above results are shown for one microphone position (at 115 degrees). All microphone results showed that the agreement between the source levels determined at 150 meters (the reference) and those at 50 meters (with a nonlinear correction) is good; generally, minor spectral differences occur, in the order of 1 to 2 dB.

For the broadband SEL results it was seen that the average difference relative to the reference is within 0.5 dB (unweighted), while the difference relative to the source strength measured some years ago (Database) is around 1 dB. For the broadband A-weighted levels, the higher frequencies, typically above 250 Hz, are more important; in this case the difference is within 1.0 dB.

6. Conclusions

A new method to determine the acoustic source strength of a muzzle blast or a detonation using large caliber weapons at a relatively short range has been described and validated through measurements.

Using a shorter distance makes the deployment of microphones around the weapon simpler and faster.

Preliminary document

Additionally, the test requires less space, allowing for greater flexibility in selecting a location.

The measurements involved shots using three different charge sizes with a 155 mm howitzer and 7 microphones positioned around the muzzle blast. The source strengths for the three charge size were determined at a relatively short distance of 50 meters and at the standard distance of 150 meters (the reference method).

At shorter distances, the nonlinear propagation of the impulsive sound must be taken into account, as it travels to greater distances (typically up to 100 or 200 meters). At larger distances, nonlinear sound propagation is negligible, allowing a linear source strength to be determined. This linear source strength is used to calculate the sound levels around military training areas.

The new method corrects the source strength measured at a short distance in order to account for the nonlinear effects associated with the propagation over larger distances. This correction is determined spectrally, using octave or one-third octave bands. The results obtained using the new method are compared with those from the reference method (at larger distances); the comparison shows good agreement regarding both spectral shape and source strength levels for the different charge sizes.

In addition, extra attention has been paid to the influence of the ground, as this can result in corrections of several decibels across different octave bands when determining the source strength. By accounting for the ground interference in the measurements, a more accurate estimate of the ground absorption between the muzzle blast and the microphone is obtained (supplementing the ground impedance measurements taken at various locations around the weapon), thereby refining the necessary corrections to obtain the linear source strength.

7. Acknowledgments

This work is done for The Netherlands Ministry of Defense (MoD-NL), within the BMW4-13 project. Measurements were coordinated and carried out by the MoD-NL and the KCWM department and this cooperation is gratefully acknowledged.

References

[1] Determination of the acoustic source strength of impulse sound by measurement, TNO report, DGT-RPT-040040, 2004

[2] Geluidmetingen nabij zware wapens (BMW4 #13) - Een meet- en rekenmethode voor de bronsterkte, TNO report (in Dutch), TNO 2025 R13191, 2025

[3] E.M. Salomons, "Analytical model for sound explosives and firearms" *J. Acoust. Soc. Am.,* vol 156, pp 2034–2044, 2024.

Preliminary document