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Sound Propagation from Elevated Sources. Results of a Dedicated Measuring Campaign

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Summary

Extensive measurements were made to assess propagation characteristics of sounds produced by blast sources similar to military weapon systems for various source heights and weather conditions. Pyrotechnic explosives were used as blast sources at heights between 0 and 300 m. Two charge sizes were used: one with a sound energy level L_Q of 162 dB(C) and a second with 139 dB(C). The test site was flat and mainly covered by grass. The microphones were at a height of 4 m, and at distances between 250 and 2000 m in 8 azimuths. The weather conditions were recorded with two SODAR/RASS systems that provided the wind and temperature profiles for altitudes up to 400 m. The recorded sound pressure waveforms were processed to produce the one-third octave band and C-weighted levels for all blasts at all measurement points. The blast sound propagation characteristics for C-weighted levels changed significantly between a ground-level blast and a blast set off at 60 m, the lowest height above ground that was used. For source heights between 60 and 300 m propagation conditions changed marginally, such that the calculated propagation parameters for this range were assumed to be constant. Acoustically, the large blast source resembles heavy weapons. The influence of up- and downwind propagation characteristics was markedly more pronounced for blast sources set off on ground than for elevated sources at 60 m or higher. During daytime (with turbulence and negative temperature gradients) the blast sound propagation characteristics are nearly the same for up- and downwind conditions, but differ with source height. During night time, there were no differences between the propagation characteristics of the ground level blast sources and above ground sources (except for the correction for ground absorption and a geometrical correction). These results were incorporated into an engineering model used to estimate military artillery noise.

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1. Introduction

In the context of noise assessments, the outdoor sound propagation applies in general to situations where source and receiver are close to ground. Guidelines for this case may be found in ISO 9613-2 [1]. For high-energy, impulsive blast sounds set off on ground, the German Ministry Of Defence (MOD) has put forward an empiric model to predict the propagation over long distances [2]. However, sound propagation for blasts set off significantly above ground is missing in the MOD's model. While there have been investigations in other countries that examine the effects of source height and weather conditions on propagation, [3] to [4], reliable measured data are needed in order to expand the German MOD's methods to the situation with sources above ground. Data from blast sound sources set off at heights of up to 300 m above ground were collected during a measurement program in 2008. These data are analysed and discussed in this paper, and a procedure is proposed to extend the MOD's methods to include above ground level blast sources.

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2. Sound prediction model

The German MOD method and the corresponding computerized prediction program "WinLarm" are based on the formulae shown below [2]. The immission sound exposure level L_{CE} at a distance d from the source is calculated from the emission sound level $L_{CE,250\mathrm{m}}$ plus the angle-dependent directivity minus several distance-dependent attenuation levels,

$$L_{CE}(d,\alpha) = L_{CE,250\mathrm{m}} + D_{dir}(\alpha) - \left[D_{dis}(d) + D_{abs}(d) + D_{sit}(d) + D_{met}(d)\right], \quad (1)$$

with

$L_{CE,250m}$: The emission sound level in 250 m is calculated according to [5].

$D_{dir}(\alpha)$: Directivity pattern of the emission sound level $L_{CE,250\mathrm{m}}$ as a function of sound radiation angle α between the propagation direction and the shooting direction.

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$D_{dis}(d) = 20\,\mathrm{lg}(d/250\mathrm{m})$: Sound level reduction by geometrical spreading.
$D_{abs}(d) = \beta_0(d - 250\mathrm{m})(d/1\mathrm{m})^{\beta_1}$: Sound level reduction due to air absorption.
$D_{sit}(d) = -K_{lin}(d - 250\mathrm{m}) - K_{log}\,\mathrm{lg}(d/250\mathrm{m})$: Sound level reduction due to other factors that have an effect on sound propagation like the ground effect (linear and logarithmic excess loss).
$D_{met} = -(0.0012 + 0.042 v_{\mathrm{Wind}}/v_0)K_{met}\,\mathrm{lg}(d/250\mathrm{m})$: Sound level reduction due to meteorological influence with v_{Wind} = Wind speed in m/s (with consideration of weather inversion +2,37 m/s) and $v_0 = 1$ m/s.

In this model, the distance d is the horizontal distance between the blast source and the receiver.

In the MOD method, the various attenuations of blast sounds with distance are calculated relative to a distance of 250 m, and the dependence of the blast source directivity as a function of α is calculated relative to an angle of 135°. For omni-directional sources, measurements in different directions are considered to be independent samples of the omni-directional source, and hence are averaged on an energetic basis. The MOD method accounts for weather conditions with inversions by increasing the wind speed with the constant value of 2.37 m/s to increase the resulting L_{CE} [2].

A method to determine the model parameters in the MOD method was published in 1995 by Buchta [5]. In the model, the decay of blast sounds with distance is based on a curve-fitting process. In [6], Hirsch states that the blast sound propagation parameters used in "WinLarm" are based on the 90th percentile of all possible propagation conditions, and that 50% of these propagation conditions are supposed to be downwind. This leads to the result that the 90th percentile of all dispersion conditions corresponds to the 80th percentile of all downwind conditions. Therefore, in this paper the 90th percentile levels are used for investigations of angle independent immission levels (sections 5.1 to 5.4), and the 80th percentile levels for angle sensitive investigations, e.g. the influence of wind on propagation (section 5.5).

The emission sound level at 250 m $L_{CE,250\mathrm{m}}$ is determined by the MOD method in its directive [7] in 250 m based on measured sound levels. Typical values for the coefficients are

$K_{lin} = -1$ dB/km	(linear propagation coefficient),
$K_{log} = -7$ dB	(logarithmic propagation coeff.),
$K_{met} = 20$ dB	(meteorological propag. coeff.),
$\beta_0 = 0.5$ dB/km	(1st absorption coefficient),
$\beta_1 = 0$	(2nd absorption coefficient).

Both absorption coefficients are given in terms of the fundamental frequency of the blast source spectra, and the change in this frequency with distance. The value of 0.5 dB/km for β_0 corresponds to a fundamental frequency of about 160 Hz. With a value of zero for β_1, there is no change in the fundamental frequency with distance because in this case the effect of air absorption is low compared to other influences. The meteorological propagation coefficient K_{met} is determined from the differences in propagation levels between up- and downwind conditions. K_{met} is supposed to be dependent on the height of the blast and on the other two coefficients K_{lin} and K_{log}.

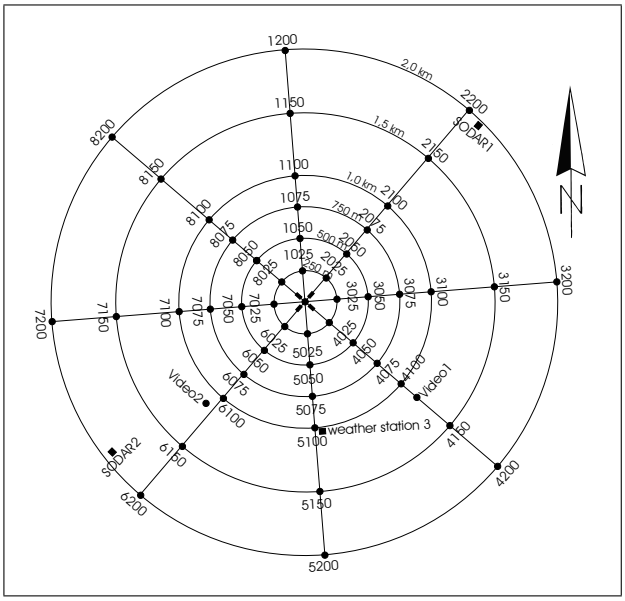


Figure 1. The measurement array with distances up to 2000 m (49 microphones, 3 meteo stations, 2 videos).

3. Measurements and data processing

The measurement program was conducted at the German Army Technical Centre for Weapons and Ammunition (in the WTD91-area) in Meppen, Germany, during spring 2008. The measurements were done in conjunction with The Swiss Federal Laboratory for Materials Science and Testing, (EMPA), the German Aerospace Center, Institute of Aerodynamics and Flow Technology (DLR) and the noise control team at WTD91.

3.1. The measurement array

Free explosions in the air at heights of up to 300 m produced blast sounds with well-defined wave forms and characteristics. The sound pressure wave forms were measured at a height of 4 m in 8 directions and at 6 distances ranging up to 2 km (see Figure 1). In addition one microphone was placed at the centre of the measurement area. Class 1 microphones [8] of 1/4" and 1/2" diameter were used. The sound was digitally recorded with 16 or 24 bit resolution. From the recordings the overall C-weighted and the one-third octave band levels were calculated for each blast at each measurement position. The blast charges were propelled by lift charges to the explosion height. At some measurement positions it was necessary to exclude lift charge blast effects by time windowing. As the main goal was to extend the MOD model, which is based on the C-weighted sound exposure level (L_{CE}), the same metric was used in the analysis herein. From these single SEL-values the required percentile was calculated.

Weather data were collected at 3 locations: two SODAR-RASS stations measured wind and temperature up to

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400 m, and one meteo station monitored wind and temperature at 10 m. The blast sound measurements were made during different meteorological conditions, including high and low atmospheric turbulence conditions.

The test site was an open, flat, mainly grassy field. Some of the measurements were on adjoining farmland. The ground impedance of the grass field and the farmland were judged to be similar.

3.2. Sources

Professional pyrotechnical equipment was used to generate the blast sounds at different altitudes up to 300 m. The ground level blasts were set off at a distance of 50 m from the central point of the array; blasts set off above ground detonated directly over the central point of the array. An advantage to using pyrotechnics as blast source is that they may be assumed to be omni-directional. Individual variations in the emission characteristics are levelled out by measuring series of the same type. One disadvantage is the imprecise prediction of the altitude. A video system was used to determine the exact blast height for each explosion. To achieve different heights we had to use two kinds of bombs, differing in explosion mass (179 grams and 510 grams) and in rocket propulsion.

The small charges were used for lower heights. In the data processing, the immission signals of the lift charges were excluded by using a suitable time window function. The peak of the unweighted sound energy spectrum was around 100 Hz for the large blast source used and around 500 Hz for the small blast source.

Figure 2 shows the energy spectra for the two blast sources used: the large charge with a sound energy level L_Q of 162 dB(C), and the small charge with 139 dB(C). The spectra were reduced to emission data using the measurements at the central point and procedures according to ISO 17201-1 [9].

The difference between the averaged source spectra of Figure 2 is shown in Figure 3.

The spectra of the large blast size are comparable to those of heavy weapons, which are the subject of the MOD method [10] Therefore, the immission levels of the small blast charge have been adjusted to correspond to the large blast charge by adding the spectrum of Figure 3. Then the L_{CE} was calculated by applying the C-weighting to the spectrum and summing up energetically.

Some of the recorded wave forms were corrupted by low-frequency wind noise. Due to lower immission levels, measurements of the small blast charge were more affected by wind noise. This corruption is further increased if one averages a set of these wind noise corrupted levels. To minimize this corruption effect, individual measured levels that did not exceed the background level by 5 decibels were excluded from the analysis (In a few cases, a 3 dB limit was used). In terms of wind noise corruption, the 90th percentile is a much better metric than is the average level, because it is relatively insensitive to such wind noise corruption. The 90th percentile is corrupted only when 90% of the measured levels are corrupted by wind noise, or if more than 10% of the measured data are outliers.

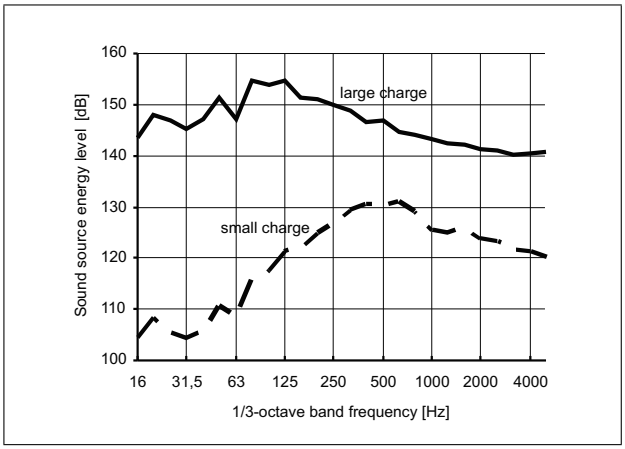


Figure 2. Source energy spectra for the two blast charges, calculated from detonations at various source heights.

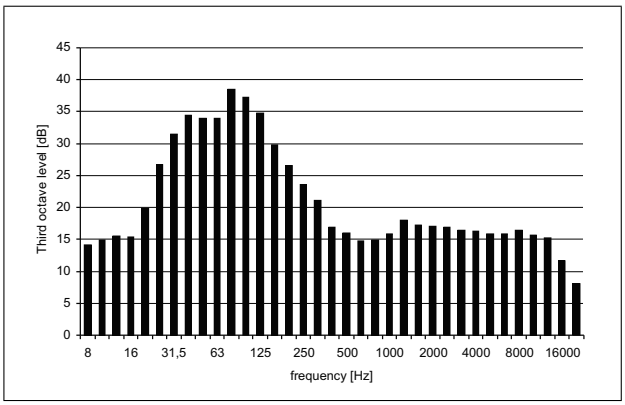


Figure 3. Averaged differences of source energy spectra of both types of ball bombs.

Table I. Weather conditions.

series	wind dir. / speed	cloudiness
1	120°/ 4–7 m/s	2/8
2	150°–180°/4–7 m/s	2/8
3	125°/ 6–8 m/s	8/8
4	210°/ 4–6 m/s	6/8
5	230°/ 4–6 m/s	8/8

3.3. Time schedule

Different time-periods were chosen to account for a variety of turbulence conditions: high, low and none. Three measurement series took place at the first day (24.4.08) from 13:50 to 14:10, from 17:00 to 17:25 and from 21:50 to 22:10, and series number 4 and 5 on the second day (25.4.08) from 13:40 to 14:00 and from 17:00 to 17:20 (GMT+2). Each series consisted of seven blocks of five blasts: one on ground, and one each at (scheduled) heights of 50 m, 100 m, 200 m, and 300 m above ground. In total, each series included 35 single blasts, which were fired at time intervals of 35 seconds.

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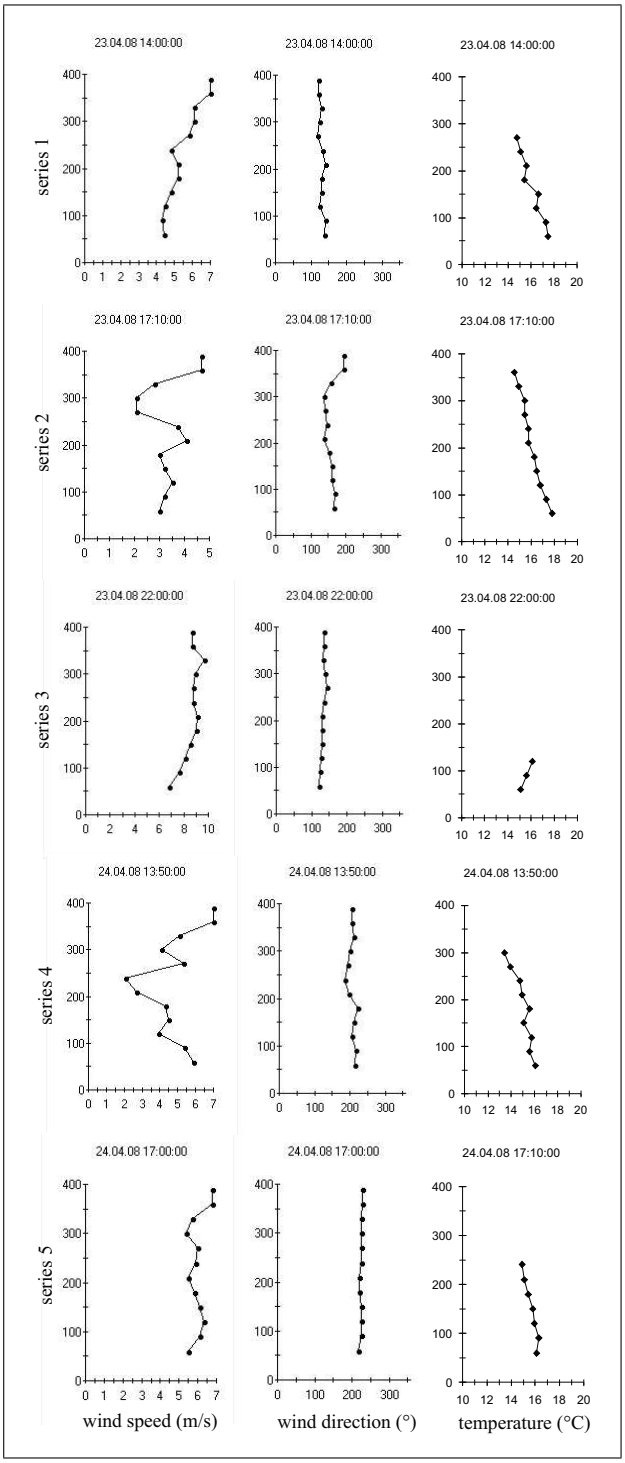


Figure 4. Mean wind speed, wind direction and temperature profiles up to 400 m for 10-minute intervals measured during the five series.

4. Measurement results

4.1. Weather

The measurement program was conducted when there was a ridge of high pressure. This resulted in a slow change in wind direction during the two days of measurement. The wind direction shifted from easterly during the first day to south-westerly during the second day, as shown in Table I.

Thanks to this change in wind direction any influence of terrain or measurement equipment on the received sound levels could be distinguished from the influence of the wind.

Sound propagation over long distances is influenced by wind profiles and the temperature stratification. According to the classification of weather situation in relation to sound propagation as discussed in [11], the situation during the measurements may be characterized as the propagation condition "unstable" for daytime and – due to the high cloud cover – as "neutral" to "stable" during night time.

The average wind gradients were rather small; even during night-time we found them to be about 2 m/s/100 m. With this type of wind gradient, the shadow zone begins at a distance of 3,2 km when the blast source is set off at a height of 300 m above ground, at 1,8 km with 100 m source height, and at 1,25 km with 50 m source height. This shows that with the measurement distances of up to 2 km, shadow zones only will be visible for blast sound sources set off at relatively low altitudes (Figure 5).

4.2. Acoustical results

The influence of the different weather conditions shown in Figure 4 can be seen in the distributions of the L_{CE} and the standard deviations for series 1, 2, and 3 in Figure 5. Nearly all the levels appear to be normally distributed, so the standard deviations in Figure 5 are calculated in decibels.

The level distributions of the averaged L_{CE} for series 1 and 2 are similar for a source height of 50 m and 200 m. For the 200 m source height the distribution is nearly equal in all directions. For the 50 m source height the influence of the wind leads to a small reduction of the levels in some areas at longer distances. Especially for the 50 m height in series 3 this area can be seen in the lower right (south-east) of the measurement area. This corresponds to the wind direction (south-easterly winds during series 3) and to the theoretical beginning of the shadow zone by the measured wind gradients as calculated above. The standard deviations are much smaller for series 3 than for series 1 and 2. This holds true for both source heights.

In average the standard deviations for the lower source height are higher than for the higher source height.

Figure 6 shows a cumulative distribution of the frequency of occurrence of the measured L_{CE} values in 2000 m not adjusted for blast size. These were used to study differences between a shadow zone and an ensonified situation as documented in [12]. The values for 300 and 200 m apply to the big blast source. Two differences are found: (1) blasts set off at heights of 200 and 300 m exhibit less spreading with distance than do blasts set off on ground or blasts set off at 100 m, and (2) distance to the shadow zone appears to have no influence on this statistical analysis.

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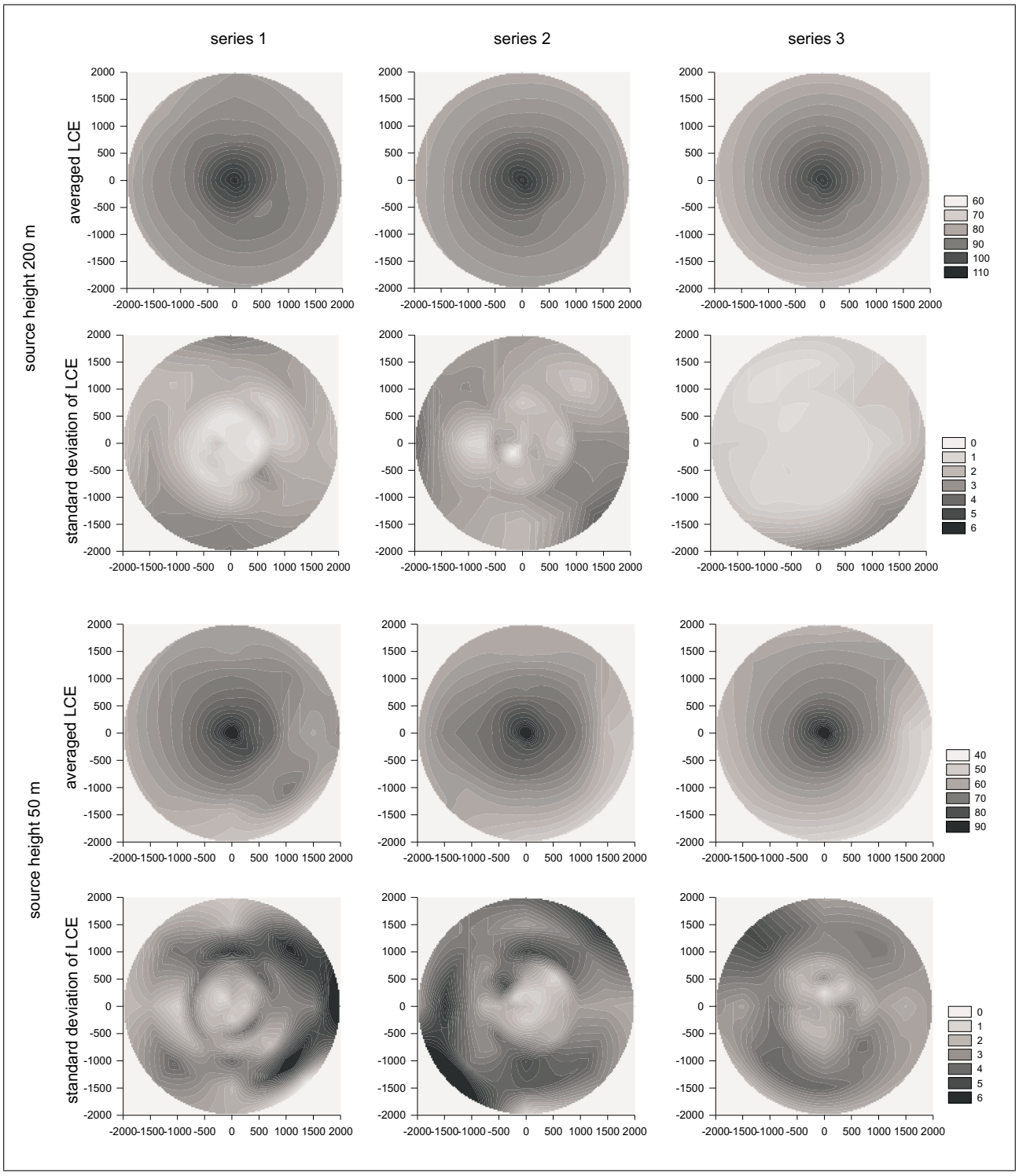


Figure 5. Contour plots of the mean L_{CE} and its standard deviation in decibels for series 1 to 3 at 200 m and 50 m source height covering a range of 4000 m × 4000 m.

In order to determine the influence of the blast source height, independently from the size of the blast source charge, the attenuation factor was calculated for the different source heights as a function of frequency.

The blast explosion heights were distributed over a wide range (see Figure 7). It was necessary, therefore, to develop a blast source height classification scheme. These classes are: 0 m (35 shots), 60 m–90 m (37 shots), 90 m–150 m (32 shots), 150 m–210 m (27 shots), 210 m–250 m (29 shots), 250 m–300 m (13 shots). Two blast sources were set off at a height that was above ground and less than 60 m; they were omitted from analysis.

If the number of blasts in the class of blast heights that were between 250 and 300 m are fewer than the number of blasts in the lower classes, the measured levels in the highest class exhibit less variation and are similar to the

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levels of the second highest class of blast heights so that even these smaller number of shots can be assumed to be sufficient for the analysis.

5. Determination of the propagation characteristics

All measured 90th percentile L_{CE} levels, depending on the classified source height, were plotted against ground distance in a logarithmic scale, so as to extract the general influence of the source height without taking meteorology into account.

For distances greater than 1000 m, the requirement that the difference between the measured level and the background level be at least 3 dB does not appear to be sufficient to prevent corruption of the ground level and the 60 to 90 m height class of blasts. A detailed examination of the immission levels for these combinations of distances and blast heights reveals only a very small number of valid blasts, and more than 10% of the levels sufficiently above background were influenced by wind noise. Because of the small quantity of valid data for the 1500 and 2000 m positions at these low blast heights, they are excluded from further analysis in this paper.

Figure 8 exhibits three main factors that affect the immission levels:

1. In the vicinity of the source, at a horizontal distance of 250 m, the immission levels of the ground and the second height class (60 to 90 m) blasts are relatively higher than are the levels for the classes with heights above 90 m. This effect decreases with increasing horizontal distance.

2. The immission levels of blasts set off at ground level attenuate more quickly with distance than do the levels for blasts set off above ground.

3. For blasts set off at heights within the second class (60–90 m), the absolute levels are about 3 dB higher at all distances compared with the levels for blasts set off at higher heights. This difference is also found for the first height class (0 m) at a distance of 250 m, but at distances greater than 250 m, this 3 dB difference decreases. This effect results from the aforementioned influence of the ground impedance on ground level blasts.

These three observations will be discussed in the next three sections.

5.1. The geometrical correction

The first factor can be explained by the difference between the ground distance used in the model and the slant distance of sound propagation between source and receiver.

The correction term only depends on the horizontal distance d between the source and receiver positions, and the height h of the source. For example, at a horizontal distance of 250 m and a source height of 300 m, the effective propagation distance is 390 m. As the air absorption for the difference in ground and slant distance is small for the low frequency dominated blast sounds, only spherical spreading is considered. This results for the example in an additional level reduction of 3.9 dB. This bias decreases very quickly with increasing distance between the source and the receiver (see Figure 9).

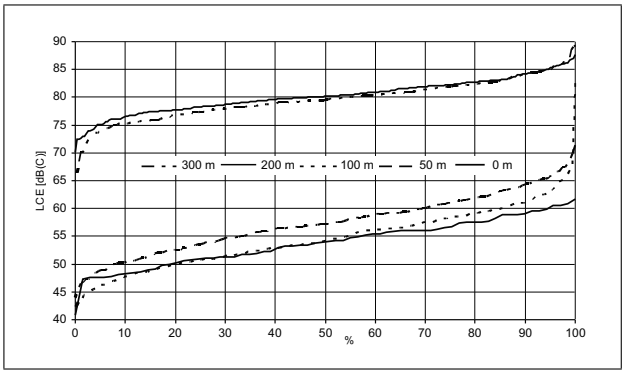


Figure 6. Cumulative distribution of the frequency of occurrence of all measured L_{CE} in 2000 m distance for the two blast charges.

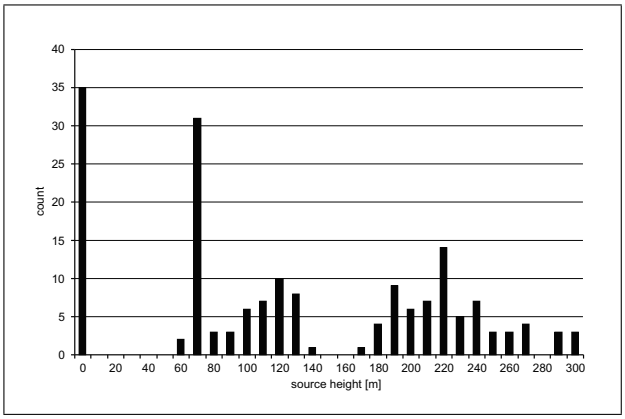


Figure 7. Distribution of the measured source explosion heights.

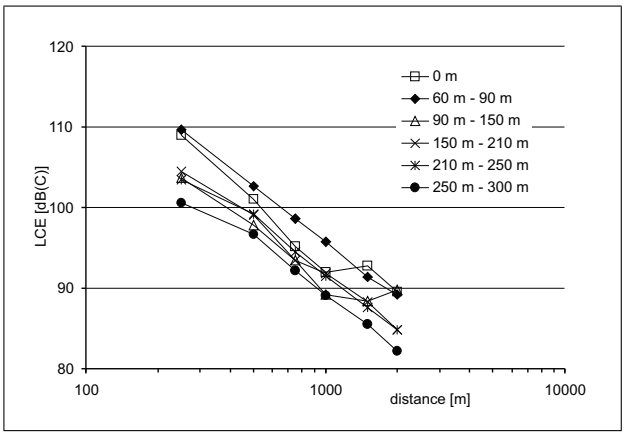


Figure 8. 90th percentiles of all measured levels against distance.

This explains about 2 dB difference in measured levels, found at a horizontal distance of 250 m, between blasts set off at a height of 210 meters and those set off at heights below 90 m.

This effect is accounted for with a correction term based on the blast height h and ground distance d,

$$L_{\mathrm{Height}}(h, d) = L_{\mathrm{Ground}} - D_{\mathrm{korr_Height}}(h, d), \qquad (2)$$

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with

$$D_{\text{korr_Height}}(h, d) = 10\,\text{lg}\left[(d^2 + h^2)/d^2\right]. \quad (3)$$

All measurement levels were adjusted with this correction, i.e. to account for the slant propagation distance, but listed in function of the ground distance. This is shown in Figure 10.

With this correction, the functions for the attenuation of blast sound immission with distance are nearly parallel to one another for all blast source heights above ground. Given the almost parallel attenuation functions, their descriptive parameters will be similar. That is, each parameter (K_{lin}, K_{log}, K_{met}, β_0 and β_1) is almost the same for all of the attenuation functions; only the emission sound level ($L_{CE,250\text{m}}$) differs.

As noted previously, for the first and second blast height classes, at distances of 1.5 and 2 km from the source, the immission levels are greatly affected by wind noise, and so they are omitted from these calculations.

5.2. The ground effect correction

The interference between the direct sound wave and the reflection off the ground is known as the ground effect. It depends on the source height, the receiver height, the distance between the source and the receiver, and the ground impedance [13, 14, 15, 16]. The geometry for the different combinations of source height / receiver height / distance were calculated and it was found that for low elevation angles of sound incidence the ground dip frequency is higher than the main frequency of the large blast of about 100 Hz; for high elevation angles the first ground dip is below the main frequency. For example the first ground dip for the center point with vertical sound incidence at 4 m height is at about 21 Hz and the second is at about 64 Hz. Ground effects increase the level at the receiver for frequencies far below the first ground dip frequency by 6 dB and for high frequencies in the average by about 3 dB.

A correction that is based on physical realities must take into account the transition between zones requiring a 6 dB correction and zones requiring a 3 dB correction. An exact solution depends on the ground impedance, the energy distribution in the source spectra and the exact source and receiver positions. This detailed data required for the exact solution is unavailable in many practical situations, and therefore we developed an empirical method for the correction for the effects of ground impedance. In our approach, we suggest no correction for source heights up to 90 m and about a 3 dB correction (reducing immission levels) for blast heights greater than 90 m. The correction is

$$D_{\text{korr_ground}}(h) = 0\,\text{dB} \quad \text{for } 0\,\text{m} < h < 90\,\text{m},$$
$$D_{\text{korr_ground}}(h) = 3\,\text{dB} \quad \text{for } h \geq 90\,\text{m}.$$

With this empirical correction we obtain the results shown in Figure 11.

When all the data are corrected using this formula, then all the above-ground level data are quite similar to one another. Only the data for blasts set off at ground level differ from the data set off at above ground level. After all of these corrections are made, an additional source factor is revealed in Figure 11. The immission blast levels for the third blast source height class are lower than are the immission levels for other blast source height classes. A more detailed examination of the data finds that for the height and distances for blasts set off in the third source

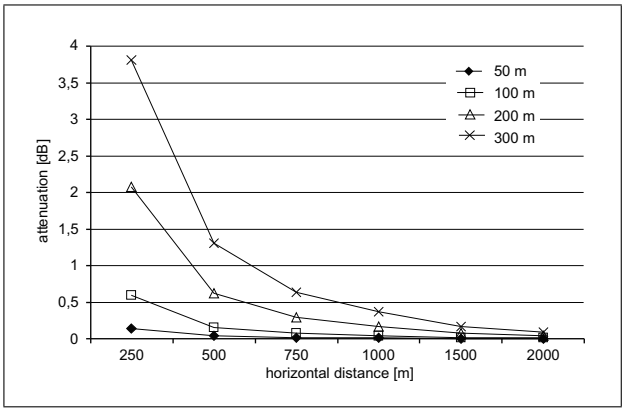


Figure 9. Values of $D_{\text{korr_Height}}(h, d)$ for horizontal distance d and four heights h.

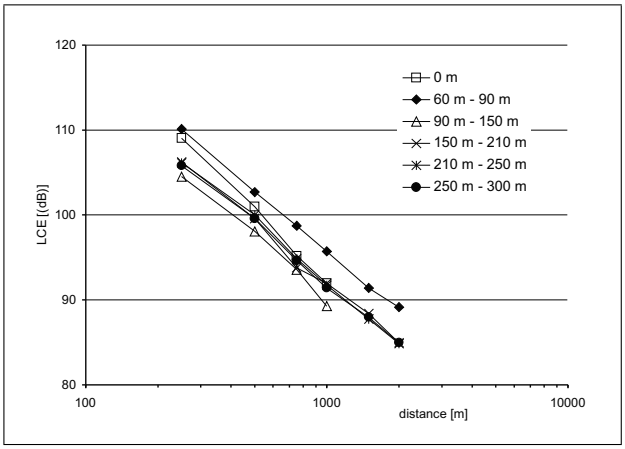


Figure 10. Slant distance corrected 90th percentile immission levels (L_{CE}) as a function of ground distance for the different source height classes indicated.

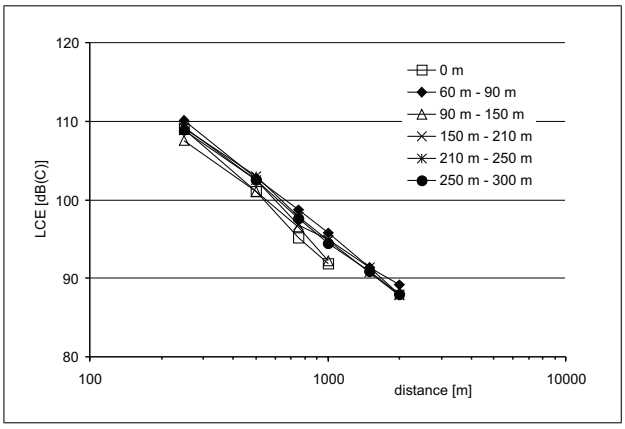


Figure 11. The L_{CE}, corrected for ground effect and height, in function of distance for various source height classes.

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height class, the spectral peak of the first ground dip is at nearly the same frequency as is the spectral peak of the blast spectrum itself. This leads to a decrease of the individual levels. This is an effect that cannot be described by this simplified correction term.

5.3. Influence of the sound propagation path

The third observation is related to the sound propagation path: the propagation path for blasts set off at ground level is close to ground. The test site mainly consisted of grassland but also included some other vegetation (50 cm tall grass to about 5 m high trees). Even if the wind and temperature gradients create a curved blast sound propagation path, the close to ground propagation encounters during a longer distance vegetation and bushes than propagation for blasts set off above ground (e.g., 60 m above ground). Therefore, the sound path of blasts set off on the ground sources exhibits greater attenuation with distance than does the sound paths for blasts set off above ground. At distances of 1.5 km and 2 km, the immission levels of blasts set off on ground are so low that they are less than three decibels above the background levels. Because the levels for these data are so close to ambient levels, they are omitted from further analysis.

As a first step, we determine the total propagation decay rate in dB/decade of distance, where the decay rate is a combination of the K_{log} parameter and geometrical spreading (20 dB/decade). The total decay rate found for blasts set off on ground is about 29 dB/decade, while a decay rate of about 24 dB/decade is found for blasts set off above ground.

We note that this 29 dB/decade decay rate is valid for the vegetation at this test site. For a site with different vegetation (e.g., a forest), the decay rate for blasts set off on ground easily could differ from 29 dB/decade of distance. The method to measure the blast sound emissions of large military weapons (e.g., armour, artillery) specifies use of an open, flat, mainly grassy field [5]. Therefore, we concentrate on a site with this type of vegetation.

As a second step, the parameters of the model described in chapter 2 are evaluated. The influence of wind is represented by the parameter K_{met}. For many weapons, K_{met} is set to a value of 20 dB. A mean wind speed of about 4 m/s was found for the overall measurement period, and a value of $K_{log} = -4$ dB was found for blasts set off at or above 60 m when using the default values of $\beta_0 = 0{,}5$ dB/km, $\beta_1 = 0$ and $K_{lin} = -1$ dB/km (see Figure 12). We must, however, note there was a high standard deviation to the wind speed data that contributed to the 4 m/s average.

The value of -4 dB for K_{log} is clearly different from the default value of -7 dB that is used in the WinLarm weapons database. This difference results from the blasts being set off at or above 60 m above ground. In contrast, for blasts set off at ground level, the value for K_{log} is found to be -9 dB in this study.

To compare these results with other measurements, Table II contains the corrected 90th percentile levels, standard deviations, decay rates, R, as functions of lateral distance from the blast, and height above ground of the blast. R is defined by the formula

$$L_{CE}(d) = L_{CE,250\text{m}} - R\lg(d/250\text{m}). \quad (4)$$

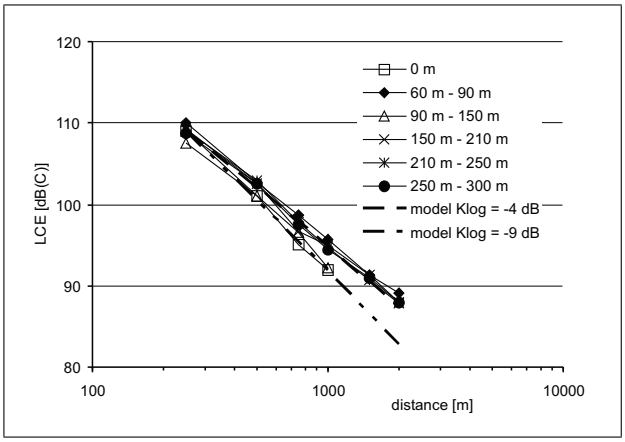


Figure 12. Corrected 90th percentile L_{CE} plotted as a function of distance versus the two distribution curves that result from using -4 dB and -9 dB for K_{log}.

Table II. For different source heights ($h_0 = 0$ m, $h_1 = 60$ m–90 m, $h_2 = 90$ m–150 m, $h_3 = 150$ m–210 m, $h_4 = 210$ m–250 m, $h_5 = 250$ m–300 m), the 90th percentile values, the corresponding standard deviations and decay rates at all distances ($d_1 = 250$ m, $d_2 = 500$ m, $d_3 = 750$ m, $d_4 = 1000$ m, $d_5 = 1500$ m, $d_6 = 2000$ m) (missing values due to high background noise).

	d_1	d_2	d_3	d_4	d_5	d_6
h_0	109.0	101.0	95.1	91.9	-	-
	2.3	2.6	2.6	2.8	-	-
	-	-26.6	-29.1	-28.4	-	-
h_1	110.1	102.7	98.7	95.7	91.4	89.2
	1.9	3.0	2.4	2.6	6.9	3.6
	-	-24.5	-23.9	-23.8	-24.0	-23.2
h_2	107.5	101.0	96.6	92.2	-	-
	1.8	2.4	3.5	4.2	-	-
	-	-21.6	-23.0	-25.5	-	-
h_3	109.2	102.6	96.7	95.0	91.3	87.9
	1.6	1.4	1.5	2.0	2.3	3.0
	-	-22.2	-26.2	-23.7	-23.0	-23.6
h_4	109.1	103.0	97.9	94.7	90.7	87.8
	1.6	1.5	1.5	1.7	2.0	2.9
	-	-20.4	-23.6	-23.9	-23.6	-23.6
h_5	108.8	102.6	97.9	94.4	90.9	87.9
	1.5	1.3	1.5	1.5	1.9	2.1
	-	-20.9	-23.6	-24.0	-23.0	-23.2

5.4. Effects of weather conditions on blast sound propagation

The effects of weather conditions on blast sound propagation are found once the effects of blast source height above ground are controlled. We expected the weather conditions to be similar during each measurement series. There were four measurement series during the daytime, and each was

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Table III. Model parameter K_{log} calculated from the 90th percentile values L_{CE}. Series 3 with correction.

	Series 1		Series 2		Series 3		Series 4		Series 5	
	h>0	h=0	h>0	h=0	h>0	h=0	h>0	h=0	h>0	h=0
K_{log}	−4	−14	−4	−12	−8	−10	−4	−10	−5	−15

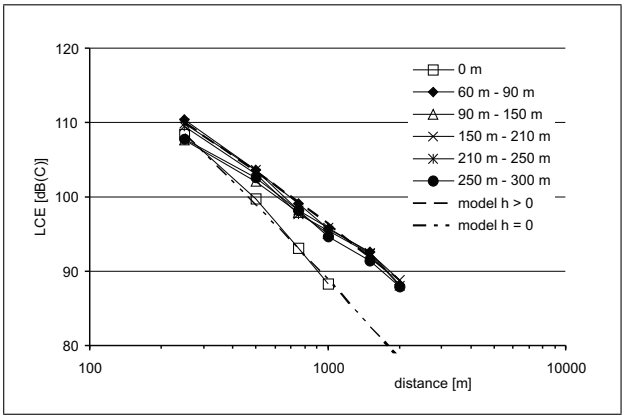


Figure 13. 90th percentile of Series 1 data (corrected for geometrical and ground effect terms).

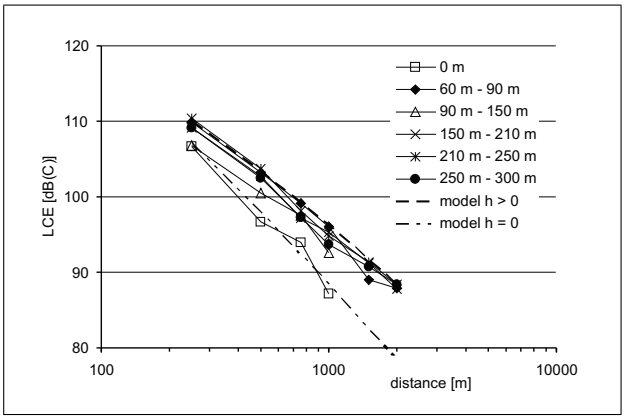


Figure 14. 90th percentile of Series 2 (corrected for geometrical and ground effect terms).

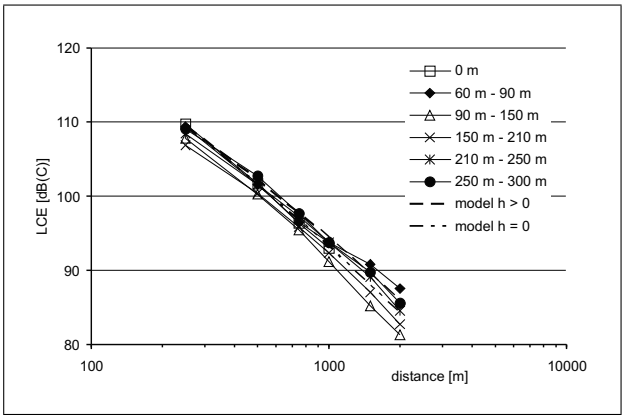


Figure 15. 90th percentile of Series 3 data (corrected for geometrical and ground effect terms).

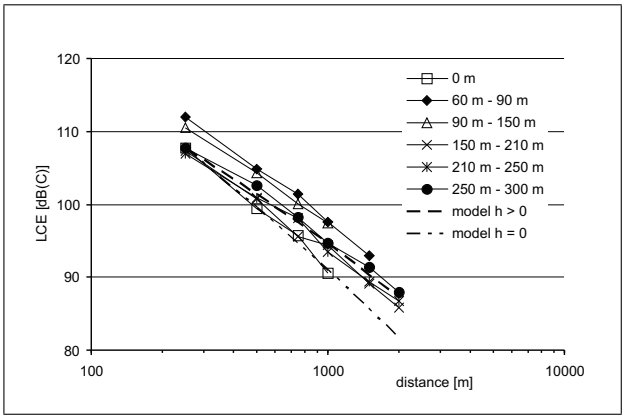


Figure 16. 90th percentile of Series 4 data (corrected for geometrical and ground effect terms, no source heights over 250 m).

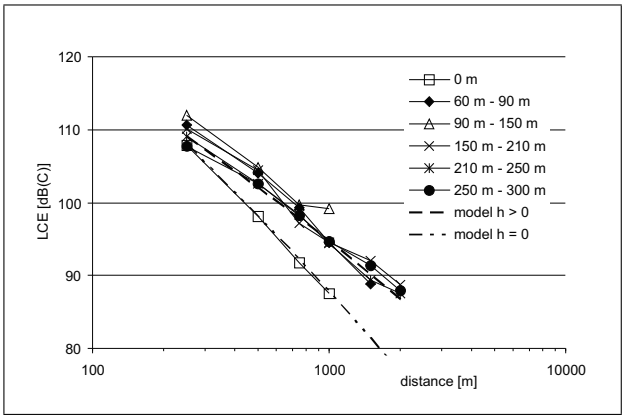


Figure 17. 90th percentile of Series 5 data (corrected for geometrical and ground effect terms). There were no blast source heights higher than 250 m.

at a time such that there should have been similar turbulent solar radiation (series 1, 2, 4 and 5), and, indeed, we found that the turbulences of all four daytime measurements were similar. There was a fifth measurement period during night when there was a laminar wind field and no turbulence (series 3).

The model parameter K_{log} is estimated for each of the five measurement series data using the wind conditions specified at a height of 6 m, and these are shown in Figures 13 to 17 and Table III, respectively. The other model parameters are set to the default values ($K_{lin} = -1$ dB/km, $\beta_0 = 0.5$ dB/km, $\beta_1 = 0$, $K_{met} = 20$ dB). The inversion condition correction was used with the series 3 data, because the night-time weather conditions warranted its use.

Data of further measurements similar to those shown in Table II are provided under http://www.ifl-acoustics.de/download/ActaAcusticaAppendix.pdf.

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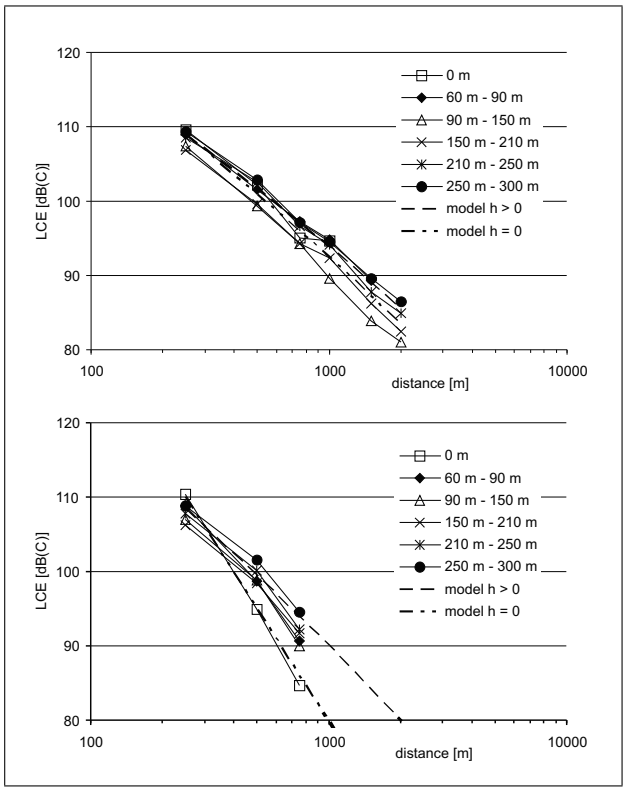


Figure 18. Down- and upwind 80th percentile levels L_{CE} of series 3.

One should keep in mind, that the values in the tables and figures herein are determined by the 90th percentile of all the data including all directions. Each single value in each graph represents the 90th percentile of about 7 * 8 = 56 data levels (L_{CE}). Hence, these underlying single levels mainly represent downwind conditions.

5.5. Effects of wind direction and wind speed on blast sound propagation

For each measurement series, we divided the data into upwind and downwind so as to extract information on the effects of weather conditions on blast sound propagation. This analysis disperses data such that only about 7 L_{CE} data points are applicable to each interpolation point. With this small number of levels, the exact value for 90th percentile has a high uncertainty. In our studies on this issue, we found that the 50th percentile is the level that is least affected by the various mechanisms that contribute to uncertainty.

The results for series 3 are included here in order to demonstrate the large difference between upwind and downwind conditions (see http://www.ifl-acoustics.de/download/ActaAcusticaAppendix.pdf for the figures that contain the same types of data for other series). These figures show that there is a significant difference between upwind and downwind blast sound propagation conditions. We find a K_{met} of about 40 dB during daytime for blasts set off on ground. For data collected during night-time, i.e., series 3, K_{met}, at about 80 dB, is much higher than the K_{met} for daytime. This result shows that the effects of wind, or lack thereof, and temperature gradient on blasts set off on ground can be much greater during night-time than during daytime. In contrast, we find relatively small values of K_{met} (0 dB to 20 dB) for elevated sources. For series 2, 4 and 5 there was no difference in the received levels between upwind and downwind conditions. In series 1 we found a relatively small value for K_{met}.

5.6. Resulting model parameters

We developed a new set of blast sound propagation functions by fitting curves to the measurement results presented in the previous section.

For meteorological conditions similar to those for series 1, 2, 4 and 5 (a high negative temperature gradient at ground level that is the result of solar radiation and a turbulent wind condition), we found the following parameter values:

$$K_{log} = -12\,\text{dB}, \quad K_{met} = 25\,\text{dB} \quad \text{for } h = 0\,\text{m},$$
$$K_{log} = -7\,\text{dB}, \quad K_{met} = 0\,\text{dB} \quad \text{for } h > 60\,\text{m}.$$

For weather conditions similar to those for series 3 (no solar radiation to cause a large negative temperature gradient; rather, black body radiation that results in a positive temperature gradient at ground level during light or zero wind conditions, or in the downwind direction), we find the values given below for K_{log} and K_{met}.

With inversion correction:

$$K_{log} = -25\,\text{dB}, \quad K_{met} = 80\,\text{dB} \quad \text{for } h = 0\,\text{m},$$
$$K_{log} = -8\,\text{dB}, \quad K_{met} = 20\,\text{dB} \quad \text{for } h > 60\,\text{m}.$$

These values were determined by using the correction for an inversion. For elevated blast sources, the inversion will have little or no effect on the blast sound propagation. As an alternative, we calculated these parameter values without the inversion correction. This results in the parameter values are given below.

Without inversion correction:

$$K_{log} = -9\,\text{dB}, \quad K_{met} = 40\,\text{dB} \quad \text{for } h = 0\,\text{m},$$
$$K_{log} = -6\,\text{dB}, \quad K_{met} = 20\,\text{dB} \quad \text{for } h > 60\,\text{m}.$$

But we have to caution the reader that, typically, these results are based on only seven events for each condition, and, therefore, have a large uncertainty.

In order to give the reader an idea of the effects of weather conditions on corresponding blast sound propagation results, Figures 19 and Figure 20 show the blast sound propagation that results from three propagation conditions with different wind speeds and wind directions.

Rather, there is black body cooling with a concomitant positive temperature gradient and little or no wind with no turbulence. This leads to a positive sound velocity gradient in all directions. Therefore there is no shadow zone at all.

5.7. Extension of the old model

A variety of model parameters have been collected for military sources over the years. These parameters are valid for the sources located on ground. If we want to use these parameters in a new model that contains the height as a parameter, we must be able to change one or more of the coefficients K_{lin}, K_{log} and K_{met} as a function of height in

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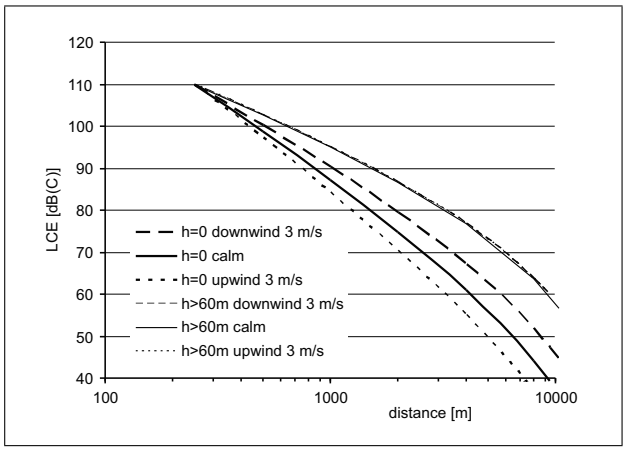


Figure 19. Down- and upwind propagation functions for situations where there is a large, negative temperature gradient on the ground (by solar radiation) and a turbulent wind situation.

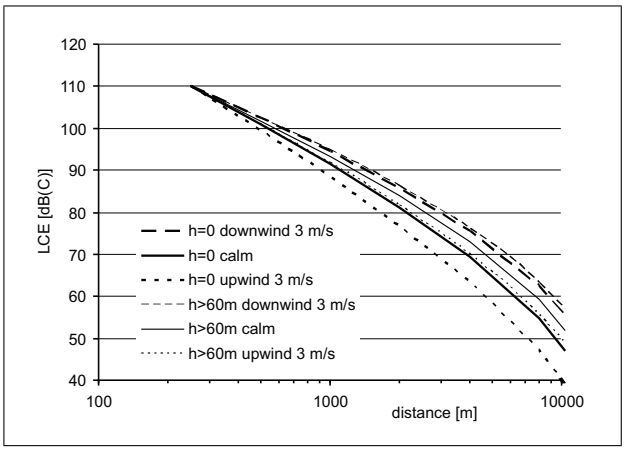


Figure 20. Down- and upwind propagation functions for situations where there is a no solar radiation.

order to use the results herein in the WinLarm program. Figure 21 shows that absolute values of K_{lin} that are larger than "1" lead to "curved" functions that are not representative of the analysed results herein, so K_{lin} is not a coefficient that should be changed to larger absolute values. There should be no additional linear absorption effects, especially for higher blast source heights. Therefore, K_{lin} should be constant with a value of -1 dB for blast source heights that are greater than 60 m.

The results found in this paper show that all the propagation coefficients are nearly constant for blast source heights that are greater than 60 m.

In order to use elevated blast source heights in the model, we must be able to continuously vary the propagation parameters from those used for blast sources set off on ground to those found in this paper for blast source heights of 60 m or more.

During this measurement program there were no blast source heights between ground level and a height of 60 m, so, we have to adopt an interpolation scheme for this range of heights. For simplicity, we have chosen a linear interpolation scheme for all parameters except for the parameter that needs to be held constant, K_{lin}.

$$K_x(h) = K_{x,\mathrm{ground}}(60\mathrm{m} - h)/60\mathrm{m} + K_{x,60\mathrm{m}}(h/60\mathrm{m}) \quad \text{for } 0\,\mathrm{m} < h < 60\,\mathrm{m}$$

and $$K_x(h) = K_{x,60\mathrm{m}} \quad \text{for } h \geq 60\,\mathrm{m},$$

where $K_x(h)$ stands for $K_{log}(h)$ and $K_{met}(h)$.

With this simple approach, we are able to add blast source heights that are above ground (greater than 0) to the WinLarm model. The extended model is

$$L_{CE}(d,h) = L_{CE,250\mathrm{m}} + D_{dir}(\alpha) - \left[D_{\mathrm{korr_ground}}(h) + D_{\mathrm{korr_height}}(d,h) + D_{dis}(d) + D_{abs}(d) + D_{sit}(d,h) + D_{met}(d,h)\right].$$

Clearly, other interpolation schemes are possible; here, for simplicity, a linear interpolation scheme is used. Future studies should focus on data for immission levels that result from blast source heights that are between ground level and 60 m. These data then can be used to determine the "correct" interpolation scheme.

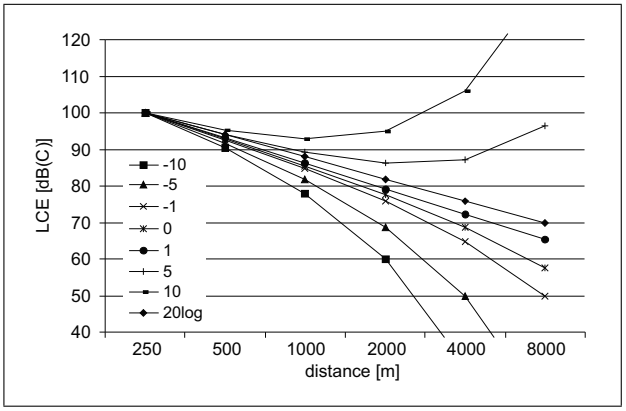


Figure 21. Propagation functions for different values of K_{lin} at 3 m/s downwind (β_0=0.5, β_1=0, K_{log} = -3 dB and K_{met} = 0 dB).

Currently, for blast sources set off on ground, WinLarm uses propagation functions that change with the source strength (blast size). In this new approach for sources set off above ground, we are suggesting that the propagation function be constant for all blast source heights that are 60 m or higher. This reduced dependence on source strength occurs because effects that depend on frequency diminish with the height of the source (shielding by vegetation, ground effects, multiple reflections and interference, etc.).

6. Conclusions

In this measurement program, a great effort was made to obtain a large number of propagation functions for different source heights and different weather conditions. These propagation functions have been analysed with respect to each and all of different variables available such as source height, immission distance, wind direction, etc.

The analysis result in a new, overall blast sound propagation function to be used in the WinLarm model. With this enhanced functional relationship, one now easily can

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adapt acoustical weapon data that were obtained using the standard measurement procedure [5] for blast sources that are set off on ground or fired at ground level, to blast sound sources that are at various heights above ground.

The main qualitative results are:

The propagation characteristics change markedly between those for blasts set off on ground, and those for blast source heights of 60 m or higher.

The immission levels are almost independent of height for blast source heights that are higher than 60 m.

The magnitude of the ground effect changes by about 3 dB in absolute immission level between the two conditions: (1) the blast source is at ground level, and (2) the blast source is at a height of 60 m or higher.

There were large differences in blast sound propagation between upwind and downwind conditions for blast sources set off on ground, and only small differences for blast sources set off at a height of 60 m or higher.

During daytime, with turbulence and a negative temperature gradient, the blast sound propagation results are nearly the same for upwind and downwind.

During nighttime, with a laminar wind field, there were no differences between the propagation results for blast sound sources set off on ground and blast sound sources set off at a height of 60 m or higher (after correction for ground effects and the geometric correction).

7. Outlook

The analysis shows that the main changes in blast sound propagation with blast source height occur when the blast source heights are between 0 m and 60 m. There were no blast source heights that were between 0 m and 60 m in this measurement program, so, the proposed interpolation scheme suggested in 5.7 is not verified and might be not the best scheme. Additional data with blast sound source heights that are between 0 and 60 m are required so that the present interpolation scheme can be verified or modified to a scheme that best fits the data.

Acknowledgement

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