On the influence of local ground reflections on sound levels from distant blasts at large distances

Karl-Wilhelm Hirsch[a]

(Received 1997 July 02; revised 1998 July 28; accepted 1998 September 05)

Sound propagation outdoors is well understood in terms of sophisticated theoretical models describing sound propagation through a layered atmosphere over finite impedance ground. Sound propagation outdoors is often surprising in terms of real measurements, for example showing sound levels from the same source changing by 30 dB over 5 min without any observable weather changes. It seems to be obvious that additional propagation effects — additional to the phenomena considered in the propagation models — cause the mismatch between theory and experiment. One of these additional effects is the influence of forest on sound propagation, directly by scattering and indirectly by changing the local meteorology between the trees and at the canopy. This was the basic motivation for a set of joint experiments on sound propagation in Norway termed the Norwegian trials. However, these trials are more important. The resulting test data can and should be used to validate blast propagation models over long distances. New analysis can be performed against these data supporting new views on outdoor sound propagation and related measurements. This paper reports an analysis of the influence of local ground effects on sound levels at different heights proving that local coherence at the receiver plays an important role in understanding receiver signals. © *1998 Institute of Noise Control Engineering.* [S0736-2501(98)00605-5]

Primary subject classification: 24.9; Secondary subject classification: 24.5

1. INTRODUCTION

For the last two decades the Institut für Lärmschutz, IfL, has worked in the field of long-range propagation of blast sounds. In 1986 and 1987 the IfL conducted a general measurement program for sound propagation of weapon blasts at the military training area of Grafenwöhr. During four measurement periods, for two weeks in each season (summer, fall, winter, and spring), about 7600 single events were recorded around the facility, analyzed and averaged with respect to acoustical levels. The results of this program indicate that the received signals include wide variations in sound pressure levels versus distance. Correlation with variations in weather conditions—recorded at the local airport—were rather weak. The Grafenwöhr results[1] justified a simple sound propagation model based on the average levels versus distance for some categories of weapon blast. This model was improved by introducing more weapon specific source information and more detailed terrain propagation data and is now used in Germany to predict the noise levels around training areas for official noise contour maps.[2,3]

However, there is continuing interest in further refinements to propagation models. An international "Ad hoc Working Group On Low Frequency Impulse Noise" initiated in 1988 by the German Ministry of Defense tries to coordinate work in this field. The experts of this group agreed that there would be no accurate propagation model for high-energy low-frequency blasts if the source measurements are not reliably performed and found to yield comparable results. The group agreed upon the CSEL as the quantity for initial consideration and proposed a so-called test plan[4] for source measurements for blasts following in general a proposal of Construction Engineering Research Laboratory, CERL, USA.[5,6]

This test plan yields reliable source data for the CSEL, but it was clear to the group that this reliability will not hold for peak pressure or spectra: The influence of the ground will disturb the measurement of the sound pressure giving unreliable results for other acoustical levels, for example one-third octave band levels. These statements have been validated for explosions from charges of 50 g.[7]

The most important argument for choosing CSEL in the test plan was that this quantity and its long-term average, respectively, are most valuable for predicting the annoyance of people living around such noise sources and this is the major goal of propagation models in this field. Though a reliable CSEL at the source is a good start for developing CSEL prediction models, more sophisticated propagation models need a source spectrum to improve their results because many propagation phenomena depend on frequency.

Sound absorption and ground reflection are two of these phenomena. Scattering and shielding by terrain also depend on wavelength. Though some sophisticated models include all these effects, a reliable database was not available to validate these models especially with respect to the prediction of low-frequency impulse sound propagation over large distances.

Therefore, a series of joint experiments focusing on blast sound propagation were conducted in Norway in order to establish a well-documented database. This database provides detailed test data[8] including pressure time histories and one-third octave spectra for the development and the validation of blast propagation models. A presentation of

[a] *Institut fuer Laermschutz, Arnheimer Strasse 107, D-40489 Duesseldorf, Germany.*

these joint experiments including a description of the test layout is presented elsewhere[9,10] and is also included in this special issue of *Noise Control Engineering Journal* including interesting results based on analysis of these joint experiments.

During the long-range trials in Norway, the blasts from various source sites were recorded simultaneously at three main receiver sites at different heights up to 30 m above ground level. These trials focus primarily on the influence of forest on the propagation of sound. However, the results are also useful for more general studies of the local influence of the ground at the receiver sites on sound levels for long-range blast propagation.

The superposition of direct sound and reflected sound from the ground normally explains that sound levels, in particular one-third octave spectra, can vary over different ground surfaces and can vary with receiver height. If there is only one clear ground reflection, this means that the receiver gets only the one direct and the one reflected signal superimposed from one single event, and a simple acoustical model—including locally reacting boundaries and sound speed gradients—can predict these variations. This model will be discussed briefly in Sec. 3.

Pressure time histories of a single blast recorded at large distances during these trials often show strange waveforms.[11] In many instances, an impulsive waveform is no longer present. The signals last for more than 10 s. The hearing impression is like a thunder from far away. The reflecting surface of the lakes around the measuring sites in Norway were disturbed by water waves during the arrival of the blast noise making the blast visible. It is well-known from observations elsewhere that high-energy, low-frequency blasts will generate rattling in houses leading to secondary noise and this justifies why prediction models for these sounds must also be reliable for low, inaudible frequency bands.

For long-range propagation of blasts the receiver is expected to collect contributions from multiple—more than two—propagation paths from a single event. There may be sound traveling on different paths from source to receiver that is originally radiated in slightly different directions and arriving at the receiver at different times. Some will propagate on so-called direct paths through the atmosphere; others will suffer one or more reflections at the ground. The ground is typically not flat and does not provide uniform boundary conditions. The fluctuation of weather conditions along the paths adds more variability. All these effects lead to the common assumption that—for a series of events—these effects should average out all influences of coherent phenomena on sound levels.

At first sight, the results obtained in Norway support this view so far as single number levels are concerned. However, without any respect to source strength or range or weather conditions, there seems to be a clear influence of the local ground at the receiver on the one-third octave spectra of the measured sound pressure. This paper focuses on the analysis of this influence.

2. GENERAL REMARKS ON THE INFLUENCE OF THE GROUND

Understanding the influence of ground reflection on the received sound pressure from blast sounds is a key to designing reliable propagation models and providing reliable source data. As mentioned above, the test plan[4] only yields reliable CSEL data while sophisticated models need the undisturbed source spectra—spectra that are not modified by ground reflection close to the source. The test layout for measuring source data according to the test plan[4] is also suitable to yield the spectrum if ground reflection is taken into account during the analysis of the recorded time histories of the pressure. Due to reciprocity, it is also important to include ground reflection close to the receiver in order to predict levels that are not affected by the specific situation at the receiver site. A counter argument to this approach is that the human ear hears the pressure signal that is affected by nearby reflectors and the ground. However for long-term average level predictions, for example with respect to large area noise contour mapping around military training facilities, the models should give a receiver level that is not dependent on a particular receiver location. This is also necessary for the prediction of the impact of blast sounds on buildings which requires more information than simply sound pressure. Therefore, the application of the prediction with respect to a special site should be a separate step. To provide test data for this application was one justification for measurements at different heights in Norway.

A. Acoustical measures at the receiver

It is important for the understanding of the following presentation that there is a clear difference in the wording, used here, for energy (flow) density, intensity, pressure square and particle-velocity square. Though these measures normally have different units, in the context of this paper they are all given as decibel levels defined relative to an appropriate base. (An in depth discussion[12] of source data descriptors of blast sounds reveals that the acoustic output power is not a feasible descriptor for shooting weapons with symmetric directivity patterns). Energy (flow) density, intensity, and pressure and velocity square are equivalent measures for a single acoustical plane wave and will give the same level in decibels if the decibel base is properly defined. Within an acoustical field consisting of more than one wave however, pressure square and velocity square do not measure intensity and intensity does not measure the energy (flow) density.

Figure 1 sketches a simple example of one direct and

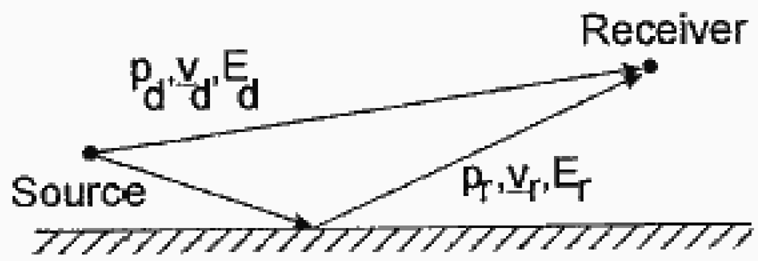

Fig. 1 – Sketch of sound rays from a point source arriving at a receiver including one ground reflection.

one reflected wave passing the receiver from a source. Then the energy E passing the receiver from a single event is the sum of the energy propagated by the direct and by the reflected wave according to the following equation:

$$\text{Energy (flow) density} = \frac{E}{\text{vicinity}} = \frac{E_d + E_r}{\text{vicinity}}. \tag{1}$$

Let p and v denote the instantaneous sound pressure and particle velocity, respectively. The word "vicinity" is meant to indicate a measure of a volume or area to yield an appropriate and convenient "density." Let index d denote the direct and index r the reflected wave quantities, respectively.

With multiple different waves—indicated through index i—passing the receiver, Eq. (1) will yield

$$\frac{E}{\text{vicinity}} = \frac{\Sigma_i E_i}{\text{vicinity}} = \sum_i \frac{\int_{\text{event}} \int_{\text{area}_i} p_i \underline{v}_i \; \underline{dA}_i \; dt}{\text{vicinity}}, \quad \underline{dA}_i \| \underline{v}_i. \tag{2}$$

In the general case of Eq. (2), the time integration covers the whole "event" and the spatial integration is restricted to an appropriate cross section called "area" with respect to "vicinity." For different waves there may be different areas.

The energy present at the receiver—that is the energy flowing through the "vicinity" during the arrival of contributions from a single blast event—does not depend on the phase shift added through the reflection at a finite impedance ground. In contrast, the intensity, the measured pressure, and particle velocity at the receiver will be sensitive to these properties because the waves will interfere.

In the example of Fig. 1, the receiver measures the superimposed pressure and particle velocity of both waves traveling in different directions. Their squares will not represent the energy flux at all, even with plane waves. Considering the distance-dependent impedance of spherical waves will add more complexity to these measures.

The intensity I at the receiver is given by Eq. (3) and is influenced by superposition of the field quantities pressure and particle velocity:

$$\underline{I} = p\underline{v} = (p_d + p_r)(\underline{v}_d + \underline{v}_r) \neq p_d \underline{v}_d + p_r \underline{v}_r. \tag{3}$$

For a monochromatic continuous plane wave, for instance, the intensity in front of a hard surface for normal incidence is zero because the intensity is a measure of the net energy flow towards and backwards from the surface. The energy (flow) density will be twice the intensity of the incident wave at any location in front of the surface. Pressure and velocity squared will alternate between $+6$ dB and $-\infty$ dB, both measured 180° out of phase. A soft surface (a pressure releasing surface) will not change anything but the phase of pressure and velocity squared. For coherent impulses of given duration, the superposition of direct and reflected sounds depends on the distance from the surface. Considering a spherical wave reflection at a finite impedance ground with absorption at arbitrary angles of incidence makes it clear that it is a real challenge to analyze the energy flow in a field near a surface. This is true even when there are only two waves making up the pressure at the receiver. Often the only information available is from a pressure measurement at the receiver site. Nevertheless, one justification for the idea of measuring at different heights in Norway was to gain information about such situations.

B. Discussion of ground models at low frequencies

In order to perform the analysis of propagation near ground surfaces, a description of the complex impedance of the ground is needed. For typical sounds physical models of the soil are available to predict this impedance. However, in the case of very low-frequency impulses such models do not provide a reliable approach because there will be a coupling between airborne sound and structure-borne sound. Compared to volume waves in ideal gases or fluids, structure-borne waves, surface waves, or shape-bound waves are governed by impedance matrices describing the interaction between shear and compression waves that defines the type of wave. Flexural waves of a window pane, for example, can provide a boundary impedance (airborne pressure to structure-borne particle-velocity perpendicular to the window pane) that matches the impedance of airborne sound waves. The observation of water waves on the reflecting surface of a lake after the incidence of an airborne blast wave confirms such coupling.

With respect to the ground response in Norway, Madshus and Kaynia[13] measured the boundary impedance at the measuring sites in Norway ranging from 500 000 to 20 000 Pa-s/m. This impedance only differs by a factor of 40 from the impedance of airborne sound waves.

As a consequence, well-known ground models are not used here so far as their physical background is concerned. Instead, an engineering formula—justified by Wempen[14] for impulse sound reflection at grassy ground—is introduced to describe the impedance. The impedance is here assumed to be proportional to $\epsilon + \eta f$ (where ϵ and η denote arbitrary complex parameters and f denotes the frequency). The parameters ϵ and η can be determined in simple propagation situations such as those in Fig. 1.

The influence of the ground on the pressure signal depends on frequency and on the angle of incidence. In general, for typically grassy ground and for small angles of incidence, the ground is a "pressure release," soft surface for higher frequencies and a "pressure doubling," hard surface for lower frequencies. Therefore, the ground reflection will shift the absolute and relative phases in the signals giving a reflected signal that is delayed and distorted in shape. A minor effect in this context is that the ground absorbs sound energy. In the most important frequency bands (lower than 200 Hz), that dominate the signals received from high-energy explosions at large distances, the absorption is in the range of 10%.

C. Angle of incidence at large distances

An additional justification for measuring at different heights in Norway was to determine the angle of incidence of the signals. This angle provides information that is useful for validation of propagation models. The angle of incidence causes a time delay from top to bottom in the sequence of pressure signals. In most cases however, in particular when the blast sites were far away (>10 km), the signals deliver significant energy during a time period of more than 10 s due to multiple path propagation. Therefore it was not possible in many signals to clearly identify signal features at each height where such a delay could be determined reliably. In cases where the analysis was possible the angle of incidence varies from grazing incidence up to 15°.

The next section will firstly demonstrate the influence of the ground on analyzing source data for a blast and discuss the resulting energy flow at the receiver. Secondly, this section introduces a simple blast source model. Such a model is also needed to understand the results of the Norwegian trials with respect to receiver height.

3. GENERAL REMARKS ON THE BLAST SOURCE DATA

A blast source is a rather simple acoustical noise source. It is particularly simple with respect to spectral energy distribution. In addition, such a source generates an acoustic impulse at a certain location at a certain time. Compared to this simplicity, a passing motor vehicle is a rather complex noise source. It is moving and the engine, the exhaust, and the wheels on the road are all contributing different sounds dependent on the velocity of the vehicle, the road condition and so on.

However, due to the coherence of blast signals, it is important to begin propagation calculations with an accurate model of the spectrum of sound pressure or particle velocity or the physical spectral energy distribution with amplitude and phase in order to understand or predict the measured propagation phenomena.

With acoustical blast models close to the receiver, it is important to have accurate estimates of acoustical source energy because the field quantities of pressure and particle velocity will be rather complex in the direct vicinity of the source. For example, the very high pressure close to the source yields nonlinearity, distorts time signals, and shifts energy in the spectral bands; but overall, energy will not be dissipated significantly near the source. From an acoustical point of view, this effect may change the energy in a one-third octave band by 100%, resulting in a 3-dB change in the acoustical measures, but most of this energy will show up in other frequency bands.

A. A simple blast source model

For a simple but sufficient far field approach, it is not necessary to include specific phenomena pertaining to the explosion, for instance the influence of various types of explosives or the nonlinear effects. A most promising acoustical source model for blasts is the so-called Weber model,[15] published in 1939. Originally deduced for the phenomena of pressure impulses generated by the release of electrical energy by discharge in a spark gap, this model has been validated in terms of acoustical accuracy for a variety of explosions in air for charge sizes ranging from 0.5 g to 20 kg by the author.[16]

The basic idea of this model is that the source of the blast is a spherical volume of compressed gas. If the sphere expands with a higher speed than the sound speed in the surrounding air, this sphere is said to explode. As long as the explosion continues the sphere cannot radiate any sound because the expanding sphere will overtake any sound wave. In this state the volume of the sphere will grow and the expansion speed will decrease. There will be a point in time when the expansion speed equals sound speed. At this moment the sphere will begin to radiate sound.

This radiation only depends on the particle velocity on the surface of the sphere not on the pressure. The particle velocity equals the sound speed, therefore the radiation per unit area is a constant in this far field model. The total radiated energy is determined by the size of the sphere at the moment of sound radiation.

The equation of state of an ideal gas is used to describe the relaxation process after the expansion speed crosses the sound speed and the radiation impedance of the breathing mode is needed to yield Eq. (4) for the pressure spectrum $\hat{p}$ of the blast[15]

$$\hat{p}(\omega)=\frac{P_W}{\pi}\left[\frac{\alpha}{\alpha^2+\omega^2}+j\frac{\omega}{\alpha^2+\omega^2}\right]. \tag{4}$$

In Eq. (4), P_W denotes the overpressure at the surface of the sphere ($P_W \cong 14.4$ kPa according to Weber[15]), and ω denotes the angular frequency. Equation (5) defines the parameter α in Eq. (4),

$$\alpha=\frac{3c}{R_W}\left[1+\left(\frac{c}{\omega R_W}\right)^2\right]^{1/2}, \tag{5}$$

where c is the sound speed and R_W is the radius of the sphere which is called the Weber radius of the source.

The Weber model works pretty well because it is founded on an energy approach and not on a description of pressure time histories though the pressure spectrum is the result. In addition, the major advantage of this model is that it adjusts the Fourier spectrum of the blast in amplitude and phase by only one parameter. Independent of the very simple view of explosions, Eq. (4) is a very reliable engineering formula for blast signals.

B. Example of blast measurement

Figures 2 and 3 show measurement and analysis results in terms of one-third octave spectra generated by a 50 g charge for downwind and upwind propagation, respectively. Both measurements were acquired simultaneously at opposite receiver sites 250 m from the source according to the rules of the test plan.[4] Each figure includes three spectra. The spectrum denoted by circles is the spectral pressure squared measured at the receiver microphone at a nominal height of 1.5 m. The continuous line gives the Weber spectrum representing the energy flow at the receiver. The spectrum shown as bars indicates the predicted spectrum at the receiver for pressure squared using the Weber spectrum as the source spectrum.

For both the direct and reflected signal, the Weber–Fourier spectrum serves as the source spectrum with the same amplitude and phase for prediction of the pressure spectrum. Both signals are numerically propagated to the receiver position taking into account frequency-dependent

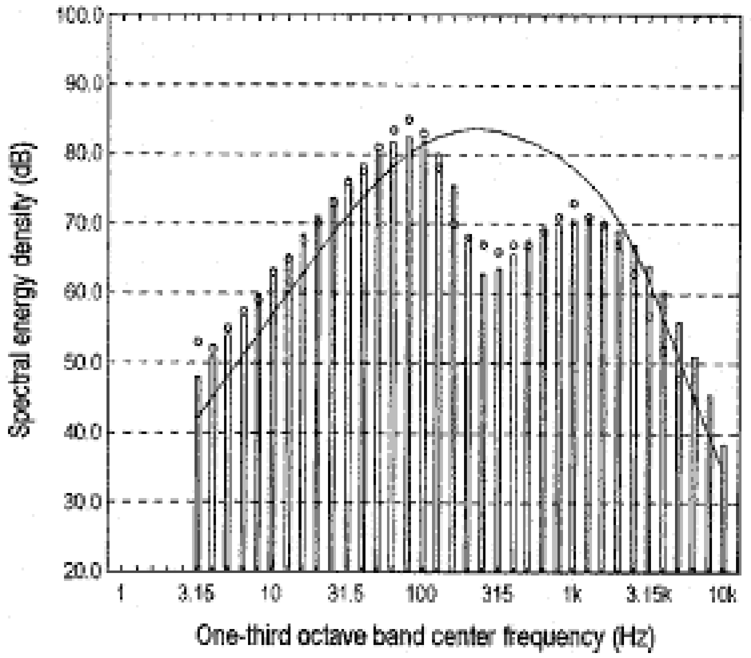

Fig. 2 – Data analysis of a 50-g blast close to the ground measured at 250-m distance and 1.5-m height, downwind propagation over an impedance ground (line—Weber spectrum energy flow: CSEL=93.2 dB, ASEL=87.6 dB; bars—predicted using Weber spectrum: CSEL=89.1 dB, ASEL=79.4 dB; circles—measurements: CSEL=89.9 dB, ASEL=79.3 dB).

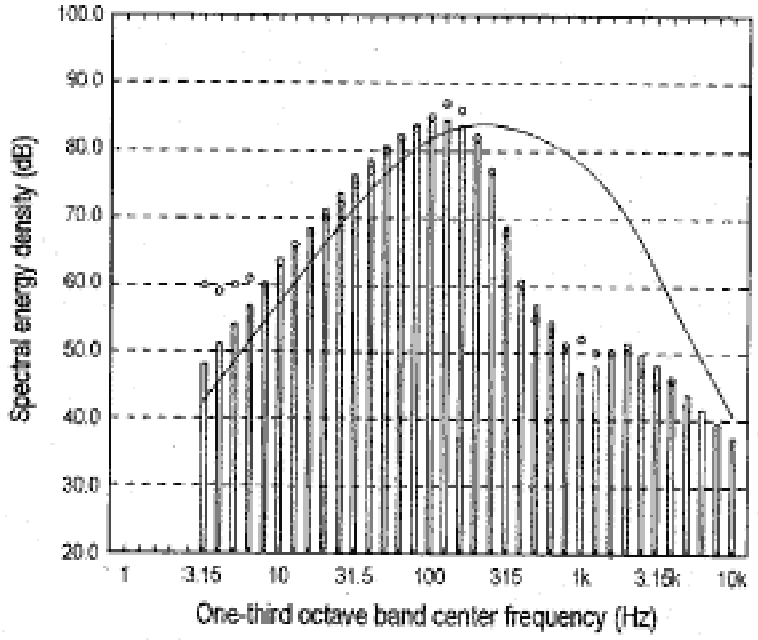

Fig. 3 – Data analysis of a 50-g blast close to the ground measured at 250-m distance and 1.5-m height, upwind propagation over an impedance ground (line—Weber spectrum energy flow: CSEL=93.5 dB, ASEL=87.7 dB; bars—predicted using Weber spectrum: CSEL=91.7 dB, ASEL=76.5 dB; circles—measurements: CSEL=92.7 dB, ASEL=77.7 dB).

air absorption and, for the reflected wave, the different path length and the phase shift during ground reflection. The procedure, of course, takes into account the reflection of a spherical wave at a plane impedance surface. At the receiver both pressure signals are combined to yield the predicted pressure signal independently from where the wave is arriving at the receiver. The pressure squared of this sum is then shown as the bar spectrum in the figures. This pressure squared spectrum should correspond to the measured spectrum, the circles in each figure.

The predicted pressure squared spectrum is very sensitive to small changes in distance, source and receiver height, the complex impedance of the ground, the wind profile and humidity because only slight phase shifts between direct and reflected waves can yield rather different spectra.[14] Therefore, in order to validate both the source model and the propagation calculation, the numerical procedure varies all propagation parameters to achieve the best fit. The variation of each parameter is strongly limited to reasonable ranges. In this case, the procedure could vary, for instance, the receiver height by ± 100 mm to find an optimum correlation for measured and predicted spectra. These heights above local ground are measurable with higher accuracy, but the prediction procedure uses 0 m altitude as the height for the point of ground reflection which means that changes of source and receiver height can include errors in the flatness of the site.

This optimization is only necessary and important for the higher frequencies. The lower frequency bands are not affected, and it is clear that the energy (flow) density, the line spectrum, is not affected at all, apart from the slight changes in levels with the variation of distance between source and receiver and the minor change of ground absorption. Therefore, the low-frequency one-third octave bands, in this case more than ten independent bands, determine the Weber-radius of the source regardless of changing propagation parameters.

Both Figs. 2 and 3 show good agreement between predicted and measured pressure squared and reveal that the blast spectrum follows a 30 dB per frequency decade increase in level at lower frequencies and a 10 dB per frequency decade decay for higher frequencies in this one-third octave presentation. Lower and higher frequencies are with respect to a relative maximum in the spectrum which is defined by the Weber radius. There are regions where the pressure is doubled. These are regions where the bars exceed the line by 6 dB. There are regions where the superposition of direct and reflected wave releases the pressure. These are regions where the bars are clearly lower than the line. However the energy (flow) density, that is the energy passing through the "vicinity" of the receiver from one single event, is a very smooth function of frequency. To underline this observation: the indicated energy (flow) spectrum in every band is necessary to explain the high and the low levels of the pressure. In the case of low pressure, the levels of the particle velocity would exceed the line by 6 dB and indicate velocity doubling.

Comparison between the two figures with respect to downwind and upwind propagation yields more interesting results. The difference in both predicted pressure squared spectra is the time delay caused by the wind speed along the path of the rays. The wind speed is a profile, so that the signal heading to the ground and then towards the receiver is accelerated less (or delayed less in case of upwind conditions) than the direct signal. This is the major effect that causes the difference between both pressure squared spectra in the figures. All other effects have the same influence on upwind and downwind propagation though the numerical procedure yields some different ground impedances during the fitting process. Even if the fitting process is not employed, the mirrored wind speed profile for upwind and downwind conditions and the related time delays causes the different shape in the observed predicted spectra. It is typical for downwind conditions that there is a dip in predicted and measured pressure squared spectra. It is also typical for upwind conditions that this dip leads to suppression of sound pressure in the entire high frequency region. This holds true for low receiver heights and grassy ground.

As a consequence for the case under consideration, the wind direction does not change the energy flow at the receiver in this 250-m measurement according to the test plan. Taking into account ground reflection and wind profile is sufficient to calculate the acoustical energy flow from the source and the Weber spectrum reliably describes the source. Both the upwind and downwind spectra yield the same Weber radius and therefore the same source data so far as the radiation of acoustical energy is concerned. Using the measured pressure squared data as input data for sound propagation models would yield incorrect results, especially in the frequency bands that are important for human hearing and noise prediction.

For example, the measured pressure squared spectra in Figs. 2 and 3, respectively, are less than 70 dB at 315 Hz. However, at both positions the receiver will measure about 83 dB if the ground is not present. Both measurements also underestimate the ASEL of the free-field signal by 10 dB. This is the total difference between the ASEL of the Weber spectrum and the ASEL of the measured pressure square spectrum. For the CSEL, this difference is about 3 dB and can be said to be an acceptable error in the context of source data from blast sounds. For higher charges the energy shifts to lower frequencies and this error in CSEL will decrease but the error in ASEL will increase. For smaller charges, measurements according to the test plan will yield unacceptable results. This is the justification for the restriction of test plan to CSEL and charges of more than 50 g.

This conclusion in general underlines the meaning of the ground reflection for measurements close to the source. The Norwegian data will show that this will hold for long-range measurement because every pressure signal at a receiver close to the ground is measuring at least a superposition of two signals, the direct signal and the local ground reflection.

4. RESULTS FROM THE NORWEGIAN TRIALS

A. Receiver signals at large distances

Any primary airborne sound at the receiving microphones must be arriving from the source directly without reflection and with positive angle of incidence. Though this seems to be a too simple statement to be made here it is worth emphasis that, as a consequence, any receiver signal at large distances is composed of a direct and a reflected part. Therefore, every receiver signal is influenced by the local ground. This local ground reflection is independent of reflections that may occur on the path of the sound wave towards the receiver site due to refracting wind and/or temperature profiles. At large distances, therefore, it is impossible to measure the so-called free-field sound directly separated by time of arrival because the angle of incidence will be small and the path differences or time delay between direct and reflected wave is also small. This also must hold true for upwind propagation conditions though the classical understanding imagines sound rays bending upwards into the sky and never reaching the ground surface. Sophisticated models overcome this problem by including scattering of sound by inhomogeneous regions in the real atmosphere. Therefore, with respect to the simple statement regarding primary airborne sound and with respect to ground reflection local to the receiver, there is no difference between upwind and downwind conditions.

It follows that the spectral "fingerprint" of the ground will not depend on the source, distance between source and receiver, type or shape of the signal. In the Norwegian trials this local ground effect should not depend on charge size, source distance, ground reflection on the path from source to receiver, airborne weather condition and so on. The discussion following later will show that this statement holds for measurements at the north and west masts.

On the other hand, the ground effect will change pressure signals with receiver height because the different path lengths between direct and reflected signals will be changing differently. Information about the ground is thus contained in the spectra at different heights. Without information about the free-field signal, a measured pressure spectrum at a certain height cannot be analyzed with respect to this information, but the difference between the spectra at two different heights at the same location must contain the information. Therefore, the following analysis uses the difference between sound pressure levels at different heights to determine the "fingerprint" of the local ground.

B. Test plan in Norway for long range propagation

As mentioned in the Introduction, detailed descriptions of the Norwegian trials are published elsewhere.[9,10] The basic idea of the trials was to measure the blast sounds at receiver sites located at the ends and at the center of a cross having 12-km-long legs to the four cardinal points of the compass.

During two 2-week measurement periods, one during summertime and one during wintertime, a series of explosions were fired daily. Each series used either 1-kg, 8-kg, or 64-kg charges. The firing positions were located along the western and northern leg of the cross at different distances from the center. During these long-range trials a lot of data were acquired for different charge weights, angles of incidence, distances, propagation paths, airborne weather conditions, and soil conditions. Stored in a relational database these data are valuable for many investigations.[8]

This paper only refers to the data measured at the west and north masts (other data were not available at the time of this analysis). At the north and west masts the microphones line up parallel to the mast at heights of 0, 1 (west mast only), 2, 4, 8, 16, and 30 m. Mounting arms hold the microphone line 2 m away from the mast perpendicular to the direction of sound incidence to avoid interaction of the sound signal with the mast itself and the small concrete platform at the base of the mast. At the central mast the lower and upper microphones were mounted to two locally separated masts, so these results must be excluded from this analysis.

All test data acquired during the Norwegian trials are stored in a relational database.[8] These data cover all available acoustical analysis (time signals for 15 s, sound exposure levels in all weightings including one-third octave spectra, peak and maximum fast weighted levels) weather data (temperature, wind speed, and wind direction at each mast at 3 different heights), and the full documentation of the experiments. All reported data (SEL and one-third octave spectra) were analyzed for a time period of 4 s out of the recorded 15 s triggered by the first clear response due to the arriving blast sound.

This method of storing data has the advantage that it is rather easy to query the database to select measurements with respect to certain conditions and combine this selection with a program to run an analysis procedure. This method was used extensively and is the basis for much of this paper.

C. Single number levels

Table 1 lists the average difference between the levels at the different heights and the level measured at 2 m for some frequently used weighted levels. The reference at 2 m was chosen for some practical reasons. This height is typical for most measurements conducted elsewhere and is well-defined. The microphone at the ground would yield some advantages as a reference and will be used to conduct a special analysis later. During the winter trials however, this microphone was used to measure at the top of the snow cover while all other microphones were located at the same positions as during the summer trials. Height in the context of this paper always means altitude above the concrete platforms at the receiver sites.

The averaging procedure includes all 227 events during the long-range summer trials in Norway without any respect to distance between source and receiver, to source location, to charge size or to wind conditions. The only condition that the levels must meet is that they sufficiently exceed background level. However, there are only a few signals that do not satisfy this condition because the background noise level is rather low (<30 dB of C-weighted energy equivalent level). Obviously, the results in Table 1 indicate that the receiver height has no significant influence on these levels. The differences are sufficiently small to say that they may be due to measurement equipment or calibration uncertainties, respectively.

This statement only holds for the average over all series including for example 8-kg blast sounds at a 1-km distance and 1-kg blast sounds at a 16-km distance. The result does not mean that for a special data group, for example 8 kg blast sounds at a 4-km distance averaged over all weather conditions and sites this statement will also hold. Such an analysis considering event groupings will be discussed later with respect to one-third octave analysis.

TABLE 1 – Average differences of single number levels to the reference level at 2-m height for the west mast and the north mast during the summer trials.

Level	ΔL_{Peak} [dB]		ΔCSEL [dB]		ΔASEL [dB]	
Location	west	north	west	north	west	north
30 m–0 m	2.29	−0.46	1.28	−0.33	−0.37	···
16 m–0 m	2.73	−1.76	1.38	−1.90	−0.33	···
8 m–0 m	2.47	−0.26	0.91	−0.59	−0.63	···
4 m–0 m	2.37	−0.13	−0.79	−0.29	−0.82	···
0 m–2 m	1.77	0.54	1.09	0.61	−1.35	···
1 m–0 m	0.93	···	−0.92	···	1.18	···

D. One-third octave spectra during summer

Figure 4 shows the average difference for the one-third octave spectra. Again the averaging procedure covers all events without any selection. The difference spectra in Fig. 4 line up in a column for the microphone heights from the top of the mast to the bottom. This section refers only to the first two columns of spectra presenting the level differences at the west mast and north mast, respectively, for all events during the summer trials. The third and fourth columns of spectra show results for the west mast acquired for the events during the winter trials and model data, respectively, discussed later.

There are some uncertainties in the data that must be considered before discussing the results. Though, due to wind noise, the average levels for the very low frequency range 1 to 10 Hz are not reliable, all spectra cover the available range of frequencies because most of the microphones used provide measurements in this range. At the west mast, only the upper microphones were low-frequency microphones which overestimates the difference levels between upper and lower heights. In addition, the acoustical energy of the blast at one-third octaves higher than 4 kHz is very low compared to the signal energy of the background noise. As a consequence, the average levels in these frequency bands are not reliable because only a few single events determine the average levels due to the requirements of the averaging procedures described above. Therefore, the discussion considering ground effects will focus on the frequency range from 20 Hz to 3 kHz.

Averaging of the differences of one-third octave spectra means treating every single one-third octave band as an independent measurement. The condition for including a level difference in the average is that each of both absolute one-third octave levels must exceed the absolute spectral background level for the band under consideration. As a consequence of this rule, each one-third octave band of the average spectra is not based on the same number of measurements.

In contrast to the average data in Table 1, there is now a clear change in levels with receiver height in the frequency range under discussion. The general pattern at both measuring sites for the summer trials is the same. The lower frequencies, 20 to 50 Hz, have higher levels close to the ground followed by a mid-frequency region showing a certain positive peak where the levels at greater heights are up to 9 dB higher than at lower heights. The left-edge frequency of that so-called peak is shifted consistently to higher frequencies from top to bottom. Simultaneously the

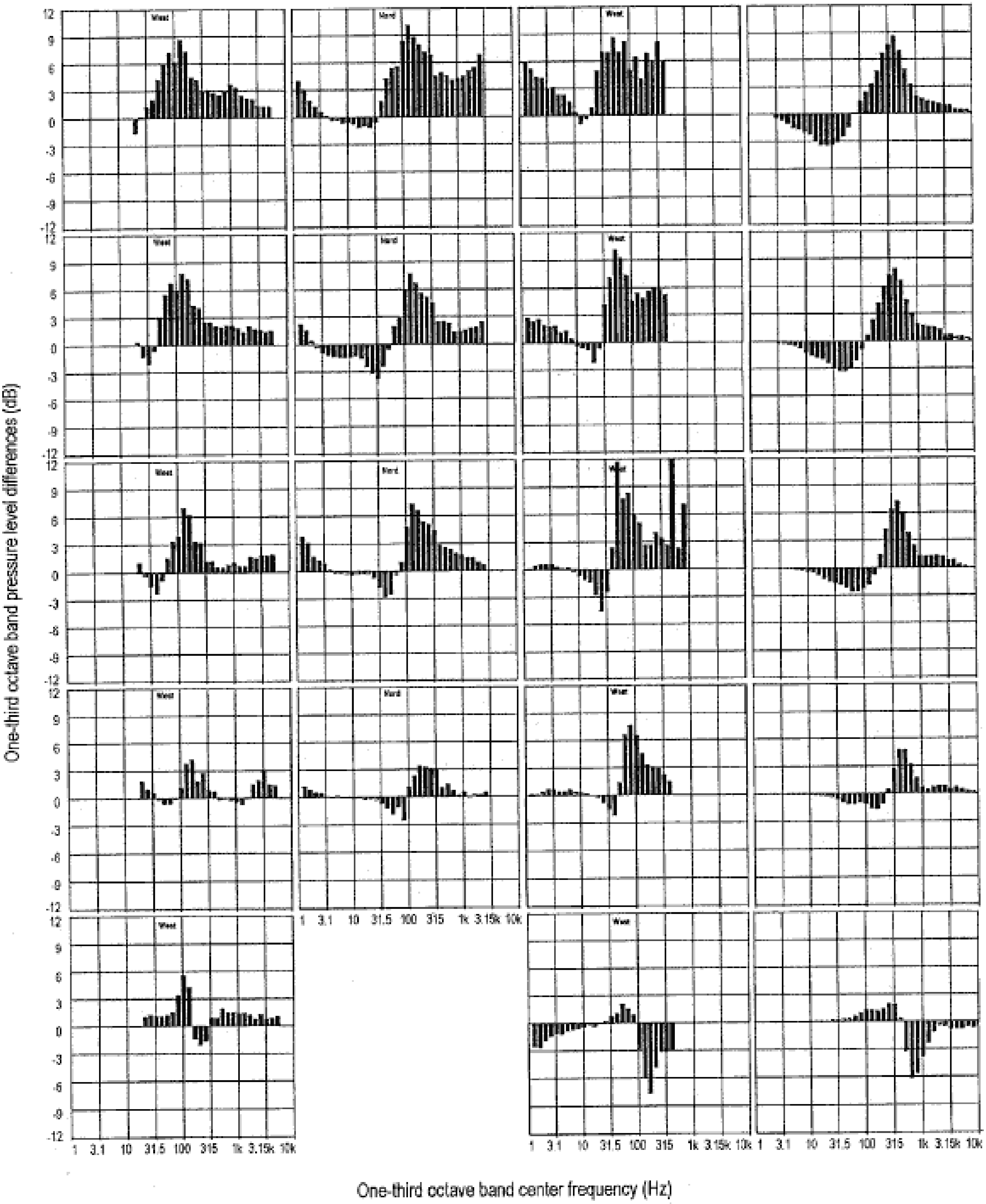

Fig. 4 – Spectra matrix of averaged one-third octave level differences with respect to 2-m height reference level. Each row shows the spectra at the same height from top to bottom position (1st row 30-m position, 2nd row 16-m position, 3rd row 8-m position, 4th row 4-m position, 5th row 1-m position). Each column represents a particular case (1st col. west mast summer trials, 2nd col. north mast summer trials, 3rd col. west mast winter trials, 4th col. theoretical approach).

magnitude of the peak is decreasing and the peak covers fewer frequency bands. These observations lead to the conclusion that this behavior is not coincidental and, because no selection has been made according to special sources or sound propagation conditions, this behavior can have a common explanation—the influence of the local ground.

E. Analysis with respect to event grouping

The results in Fig. 4 are quite consistent. However, a certain series of events grouped by any shared condition could dominate this average. For example, all data having the same wind direction could dominate this average because, due to rules for averaging explained above, upwind levels may not occur so often as downwind levels. Or with the same justification, 8-kg blast sounds are more likely to exceed background noise than sounds from a 1-kg blast. Therefore, it is necessary to analyze the average with respect to such influences. In the context of this paper, it is sufficient to present this analysis for the difference spectra between two selected heights (30 m and 0 m) for selected frequency bands (one-third octave bands at corresponding center frequencies of octaves), and for one site (west mast). The principle results for this representative case should hold for all heights and all one-third octave bands under consideration.

Figure 5 contains the results of a detailed analysis for the difference between the 30- and 0-m levels measured at the west mast for representative one-third octave bands during the summer trials. In this case, the microphone at the ground was chosen as the reference. Figure 5 compares the average for all events to the average for the group of all 1-kg charges, of all 8-kg charges, of all 64-kg charges, of all charges fired on the north–south leg, of all charges fired on the west–east leg, of all events propagating under downwind conditions and of all events propagating under upwind conditions.

In Fig. 5, the results for each group and frequency band are shown in a strip that is assigned to the center frequency of the one-third octave. The symbols denote the mean values, and the bars indicate the standard deviation for each selection and one-third octave. For some selections there are missing values in the 2- and 4-kHz one-third octave bands resulting from insufficient levels relative to background noise at either the 30-m level or the 0-m level or both.

The standard deviation is about 3 dB in the low-

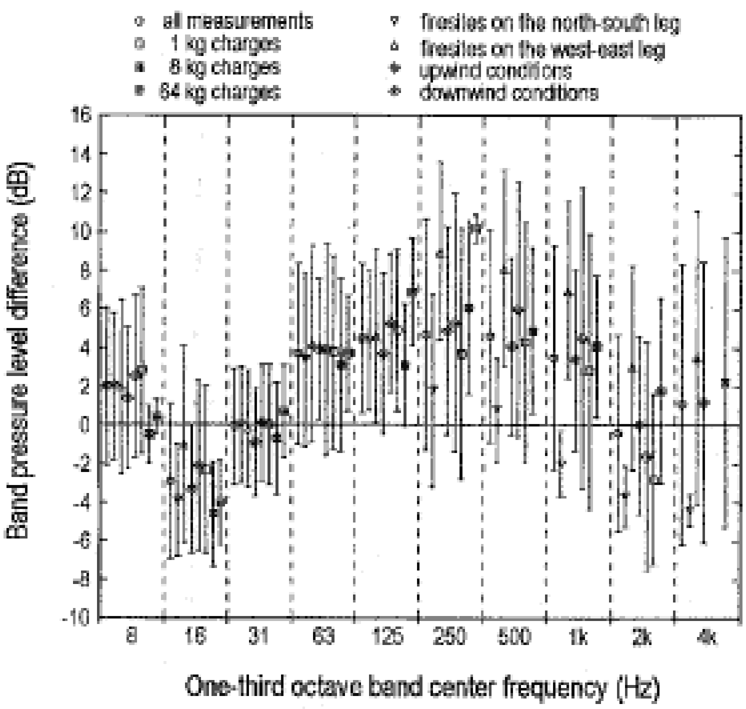

Fig. 5 – Spectral level differences between 30- and 0-m height at the west mast. Different symbols indicate different selections for source or propagation conditions. The bars indicate the standard deviation for each center frequency and selection.

frequency bands of the spectrum and increases to about 5 dB for higher one-third octave bands. The results for each selection support individually the general pattern of the overall difference spectrum. This is especially true for low frequencies up to 125 Hz. There seems to be no influence of the particular data groupings. In particular, this is a most interesting result with respect to the selections for wind conditions. Though the absolute levels downwind are clearly higher than the levels upwind, the average difference between the corresponding levels is the same. Wind conditions have a strong influence on sound propagation, but the difference between levels at different heights at large distances is not sensitive to such propagation effects.

There is one selection that diverges from the general tendency. Beginning with the 250-Hz one-third octave band, the results for the firing site selection diverge. Sounds produced by firing on the north–south leg yield approximately 7 dB higher levels than those fired on the west–east leg at the 30-m height. This representative analysis only includes measurements at the west mast. At this site, all sounds from blasts on the west–east leg have the same direction of incidence. Sounds from blasts on the north–south leg arrive from different directions depending on the blast location. Therefore, this selection is sensitive to the direction of incidence of the blast wave and may indicate the influence of terrain either in the vicinity of the mast or over the whole path of the blast wave. If shielding is responsible for this clear result, it is remarkable to note that the selection of wind direction does not yield such a difference in behavior. Normally, terrain shielding should be more effective for upwind propagation than for downwind propagation because rays for downwind propagation can "jump" over even high terrain for large propagation distances.

These results encourage a short discussion about a possible explanation for the observed difference spectra in order to prepare for the theoretical approach discussed later. For grazing incidence, typical grassy ground is known to roughly yield pressure doubling for low frequencies and pressure release for the middle and high frequency ranges (see Sec. 2). Obviously, the results in Fig. 5 support a similar assumption for the ground at the west mast during summer. The levels at the ground are a couple of dB higher at the ground than at the 30-m height. In addition, the levels at the ground are about 4 dB lower for the middle frequencies than at 30 m. This gives evidence for mixed pressure doubling and cancellation at this height.

However, these superposition effects require coherent signals but, as stated earlier, the radiated sound waves from the source should be incoherent after propagation over large distances. Therefore, the local ground reflection seems to generate coherence again for every sound wave reaching the receiver independently from the source and propagation effects along the propagation path. The angle of incidence will of course play an important role for both the effective impedance as described above and the condition of coherence. According to geometry and time delay compared to the wavelength and frequency, respectively, the coherence will decrease with increasing frequency, angle of incidence and receiver height. Therefore, the hypothesis that the local ground reflection is responsible for the results, requires small angles of incidence. Before this is discussed in the context of a theoretical approach, the results of the winter trials will be discussed to increase support for this hypothesis.

F. One-third octave spectra during winter

The third column of spectra in Fig. 4 shows the related results for the winter trials at the west mast involving a snow cover of about 0.5 m during the 2 weeks of the trials. In these tests, low-frequency microphones were used at all heights. This reduces the problems within the very low-frequency range. Only the 30- and 16-m heights seem to be disturbed by wind noise in this range. However, the high frequency range is now missing due to too low absolute levels down at the reference height of 2 m. Nevertheless, there is still a clear result.

In general, the so-called peak again occurs consistently after a frequency region where the levels close to the ground are higher than those at greater heights. The peak is broader now, more distinct in level, beginning steeper but still showing that shift of the left edge of the peak to higher frequencies from the top to the bottom position. The levels in the mid-range frequencies are 6 dB higher at 30 m compared to the 2-m reference. The comparison between 30 m and 1 m yield 9-dB to 12-dB differences when averaged over all events.

The difference between 30-m levels and 2-m levels is on the average about 5 dB greater with a snow cover than in summer conditions. This confirms the common observation that it is significantly quieter close to snow covered ground.

The winter trials in general repeated the summer trials. The winter data also includes various weather conditions and the same sequence of series of charges fired at the same sites. Though weather can never be repeated, the only consistent change to the layout of the trials between summer and winter is the snow cover. The snow cover will primarily change the effective ground impedance. Therefore, the variation in the difference spectra in general can be assumed to be produced by this ground effect through the different interference of direct and reflected sounds.

There are some conclusions that can be drawn from this observation. If this assumption is valid, then the level reduction over snow at low measuring heights is partially a local phenomenon, not due to the propagation but to the reception of the sounds from large distances. This effect should be independent of distance as long as the angle of incidence is preserved.

As a consequence, the level reduction over snow should not depend on distance between source and receiver if this distance can be called "large" which means at least 1 km in this context. This is a conclusion for absolute levels drawn from the analysis of difference levels between different receiver heights. Figure 6 supports this view for the events from 1-kg blast sources. The plot shows the average CSEL versus distance to source measured at the west mast at 2-m height for summer and winter ground conditions. The difference between these levels does not change consistently with distance and is approximately 4 dB. The snow effect observed here is obviously not dependent on

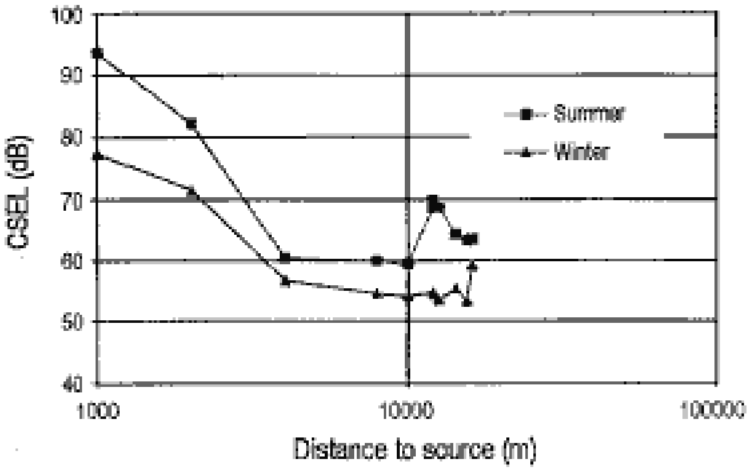

Fig. 6 – Average CSEL versus distance for 1-kg charge events for summer trials and winter trials at the west mast.

distance. The levels are reduced locally and not by propagation.

It should be noted, that this conclusion could not be based on the measurement of absolute levels in the Norwegian trials alone. There is evidence that explosions over a snow covered ground are less effective with respect to acoustical radiation power than over normal ground. Thus the source level itself could be different between the summer and winter trials, but this is not certain at this point. In conjunction with the analysis of difference levels however, the result is clear.

5. NUMERICAL APPROACH FOR THE DESCRIPTION OF THE AVERAGE DIFFERENCE SPECTRA

As mentioned in the Introduction to this paper, the effects of ground reflections on one-third octave pressure spectra are well-understood. A numerical procedure[7] can reliably predict the receiver spectra of blasts considering a valid source spectrum, see Figs. 1 and 2, but only if one ground reflection needs to be taken into account. In order to get a good correlation between measurements and numerical predictions, the procedure must consider spectral air absorption with respect to absolute air humidity, even small signal delays due to temperature and wind profiles, and the reflection of spherical waves at a plane impedance ground. Nevertheless, the same numerical procedure is used here as an approximate method to predict the average spectra at large distances at different heights.

The procedure does not accurately consider weather conditions. It only takes into account the delay of the rays due to different sound speeds at different heights not their deflection. For long range propagation, the deflection determines the angle of incidence which is most important for the coherence between the direct and the locally reflected sound. In order to use the simple procedure with straight rays, the angle of incidence at the long range receiver site is modelled by the variation of an artificial source height. In addition, multiple rays arriving at the receiver site from one single event are ignored.

During the summer trials, 227 charges were fired with charge sizes from 1 to 64 kg, at distances (relative to the west mast) of 1 to 16 km. The angle of incidence was observed to range from nearly grazing incidence up to 15°

(see Sec. 2). The numerical procedure uses these conditions to calculate the sound reflection at a plane impedance ground and predict the receiver spectra for the sound pressure squared at each receiver height. The result for each single event is as shown in Figs. 2 or 3. Then the average difference spectra for the different receiver heights are calculated.

The fourth column of spectra in Fig. 4 gives an example of the results of such a numerical approach. The spectra show the spectral level differences averaged on 227 single blasts. The procedure randomly determined the source size (Weber radius 1 to 5 m to simulate blast spectra from 1 to 64 kg blasts), the distance (1 to 16 km) and the source height (1 to 5 m) to simulate the events of the Norwegian trials. The first two criteria are determined with equal probability in the given range. The source height was forced to yield a distribution of incidence angles that strongly stresses grazing incidence. The example in Fig. 4 actually yields 52% of the angles between 0° and 3°, 23% between 3° and 6°, 10% between 6° and 9°, 5% between 9° and 12° and the rest having greater angles up to 30°. The impedance was chosen to represent typical grassy ground, the air absorption was taken into account, the speed of sound was assumed to be constant with height above ground.

The predicted results are in excellent agreement with the corresponding test data in the first column of Fig. 4 so far as the main features are concerned. First of all, the numerical results predict a change in spectra with height and do not average it all out. They predict the so-called peak, though at higher frequencies. They also confirm the shift of the left edge of the peak from the top to the bottom position. They even predict the magnitude of the peak and the increase with height.

In addition, the numerical prediction is rather sensitive to additional changes in other parameters of the procedure. For example, a random variation of one of the impedance parameters that determines grassy ground, but still forced to represent realistic ground, yields no significant average difference between the spectra at different heights.

As a conclusion, the numerical procedure supports the view that the spectra at long-range receivers for blast sounds are determined by the local ground properties. Furthermore, the numerical results, as in Figs. 2 and 3 predict approximately the same energy (flow) density for each single event at each height. That means that sound pressure levels measured at low heights strongly underestimate the spectral acoustical energy present at the receiver. This conclusion yields the same consequence as indicated during the discussion of Figs. 2 and 3.

6. CONCLUSION

The comparison of one-third octave spectra measured at different heights at different long-range locations and for two different ground conditions reveals that the ground in the vicinity of the receiver has a significant influence on the sound pressure at the receiver. If this hypothesis holds true, the impedance of the ground in the vicinity of the receiver is the key to understanding the measured pressure signals. And as a consequence, the sound pressure levels are not the direct key measure to understand blast sound propagation over long distances.

The reason for the second statement is that the so-called energy equivalent sound levels (which actually means levels equivalent to signal energy) like SEL or one-third octave spectra based on sound pressure measurements, do not measure the acoustical energy and cannot do so outdoors, because free-field conditions never exist.

With respect to long-range sound propagation models of blast sound, this conclusion means that the models should not attempt the prediction of pressure levels and should not rely on such measurements for validation neither close to the source nor at large distances. Propagation models should firstly predict energy-equivalent levels, equivalence in terms of acoustical energy, because pressure signals are locally produced and are sensitive to the local ground impedance. In addition to energy levels, the models should secondly predict the distribution of incidence angles for weather variations. For noise assessment purposes, both steps are needed to forecast long-term expected values for weighted exposure levels above the ground at the site of interest. The second step is mandatory if the prediction is to correlate with annoyance because the human ear is sensitive to sound pressure. In order to predict rattling or the impact of blast sound on houses, the second step must be modified with respect to the coupling of the low frequency components to structures. Though this proposal sounds complicated, it really makes modeling easier because there is a conservation law for sound energy, there is none for pressure squared.

7. ACKNOWLEDGMENT

This research was supported by the German Ministry of Defense.

8. REFERENCES

[1] K.-W. Hirsch und E. Buchta, "Zur Schallausbreitung tieffrequenter Impulsgeräusche über große Entfernungen," *Fortschritte der Akustik—DAGA '89*, Bad Honnef, DPG-GmbH 1989, pp. 539-542.

[2] German Ministry of Defense: "Entwurf: Bestimmungen zur Ermittlung and Beurteilung von Geräuschimmissionen durch Schüsse mit großkalibrigen Waffen und durch Sprengungen."

[3] K.-W. Hirsch and E. Buchta, "zum Standardverfahren für die Berechnung der Schallimmissionen in der Umgebung von Truppenübungsplätzen, *Fortschritte der Akustik—DAGA '93*, Bad Honnef, DPG-GmbH 1993, pp. 656-659.

[4] Ad hoc Working Group On Low Frequency Impulse Sound: "Standard Method to Measure the Sound Exposure Emissions and Immissions from Large Weapons," Fortschritt-Berichte VDI Reihe 8 Nr. 559, Editor E. Buchta, Düsseldorf, VDI Verlag 1996.

[5] P. D. Schomer *et al.*, "Acoustic directivity patterns for army weapons: Supplement 2," U.S. Army Construction Engineering Research Laboratory Report N-88/07, Champaign, IL 61826 (1988).

[6] P. D. Schomer *et al.*, "Blast Noise Prediction" Volume I: "Data Bases and Computational Procedures," U.S. Army Construction Engineering Research Laboratory Report N-88/07, Champaign, IL 61826 (1991).

[7] E. Buchta and K.-W. Hirsch, "Physikalische Aspekte zur Begründung der Wahl der C-Bewertung zur Beurteilung hochintensiver Knallgeräusche," *Fortschritte der Akustik—DAGA '96*; DPG GmbH, Bad Honnef 1996, pp. 294-296.

[8] M. Trimpop and K. W. Hirsch, "On the advantage of relational data structures and client/server applications for shooting noise data using

ODBC, SQL and OLE standards,'' *Proc. INTER-NOISE 96*, edited by F. Alison Hill and Roy Lawrence (Noise Control Foundation, Poughkeepsie, New York, 1996), Vol. 2, pp. 545–548.

[9] R. Guice and A. Jensen, ''Impulse noise measurements in a forest during summer and winter conditions—an overview of measurements,'' *Proc. INTER-NOISE 96*, edited by F. Alison Hill and Roy Lawrence (Noise Control Foundation, Poughkeepsie, New York, 1996), Vol. 5, pp. 2589–2594.

[10] G. Kerry, ''An overview of the long range impulse sound propagation measurements made in Norway,'' *Proc. INTER-NOISE 96*, edited by F. Alison Hill and Roy Lawrence (Noise Control Foundation, Poughkeepsie, New York, 1996), Vol. 2, pp. 583–588.

[11] M. J. White, ''Forest soundings: Interpretation of pressure waveforms of explosions at distances up to 20 km,'' *Proc. INTER-NOISE 96*, edited by F. Alison Hill and Roy Lawrence (Noise Control Foundation, Poughkeepsie, New York, 1996), Vol. 2, pp. 555–560.

[12] K.-W. Hirsch, ''Messungen der Emissionsdaten von Mündungsknallen,'' Schalltechnik 98, VDI Berichte Nr. 1386, VDI Verlag 1998, pp. 159–174.

[13] C. Madshus and A. M. Kaynia, ''Ground response to propagation airblast,'' *Proc. INTER-NOISE 96*, edited by F. Alison Hill and Roy Lawrence (Noise Control Foundation, Poughkeepsie, New York, 1996), Vol. 3, pp. 1433–1438.

[14] J. Wempen, ''Schallausbreitung über Erdboden,'' Dissertation Universität Oldenburg, Bibliotheks-und Informationssystem der Universität Oldenburg, Oldenburg 1991.

[15] W. Weber, ''Das Schallspektrum von Knallfunken und Knallpistolen mit einem Beitrag hber die Anwendungsmöglichkeiten in der elektroakustischen Meßtechnik''; Akustische Zeitschrift 4 (1939), pp. 377–391.

[16] K.-W. Hirsch, ''Emissionskennwerte von Waffenknallen,'' *Fortschritte der Akustik—DAGA '98*, Zürich, Verlag: Deutsche Gesellschaft für Akustik e.V., DEGA (1998), pp. 188–189.