Absorption of blast sound close to the source

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Abstract

The firing of weapons or demolitions for training purposes normally takes place at dedicated sites. Commonly used, pre-defined training scenarios result in repetitive blast emissions. In many cases, these emissions are dominated by reflections of the blast sound from surfaces close to the weapon or from obstacles that are present at the site during firing. The ground is one of these reflecting surfaces, a safety baffle is another example. As a consequence, sound at receiving sites can be dominated by the reflected sound at the source. Therefore, noise abatement measures applied to reflecting surfaces close to the muzzle of a gun or close to a demolition can very effectively reduce the sound at receiver sites.

Close to a blast source, the acoustical levels are very high and the rules of linear acoustics do not necessarily apply for absorption phenomena. In order to develop noise abatement measures close to a blast source, tests were conducted using small demolitions (50 g) and muzzle blasts of a pistol shooting blanks. This paper reports on tests that investigated the use of mineral and steel wool for blast sound absorption. One major result is that the benefits of absorbing materials near to the source are limited by the significant reflections of the blast at the surface of the absorbing material.

As a consequence, this paper discusses two ways to reduce this effect: One way is to use a pile of layered absorbers with the density gradually increasing from layer to layer to match the impedances of air and absorbing media. The second way is to guide the sound through a so-called 'Multiple-Screen-Absorber' , in which the sound suffers multiple reflection at absorber surfaces before it is set free.

1 Introduction

Sound abatement measures close to the source are normally preferable to those measures along the propagation path or close to the receiver sites. For large military guns in the field such measures are normally impossible because the missions for training purposes must meet military requirements and cannot interfere with the goals of training. However, at dedicated firing positions pre-defined training scenarios result in repetitive blast emissions. At such positions it may be possible to apply sound abatement measures.

One possible measure for large gun muzzle blasts is a muffler. This rather effective device /1/ is expensive and needs automatic systems to control the position of the muffler in front of the barrel during normal operation. Therefore this solution is only applicable at a few firing positions where it is more expensive to stop the use of this position at all than to pay for an expensive silencer. The authors know of only two facilities where such a device is in use today.

A second option may be placing absorbers and walls behind the weapon in order to mitigate the sound radiation to the rear of the gun where most of the areas requiring protection are located. Such a measure should be supported by an additional option of reducing the ground reflection from beneath the muzzle. The placement of absorbers close to the muzzle blast of a large gun must consider the high pressures and high temperatures.

For small arms different conditions apply. At least for German military small arms firing ranges, the safety measures incorporated into the structural design include baffles across the firing lanes at selected positions relative to the position of the shooter. For the muzzle blast and the projectile sound, these baffles are large reflectors that direct sound to the rear of the line of fire. Due to the high directionality of the muzzle blast of rifles and pistols, these reflections dominate the received level in residential areas that are typically located to rear of the range. Therefore, one option to significantly reduce the noise level at such locations are abatement measures applied to these reflecting baffles. Again, if the baffles are close to the shooter, the layout of these measures should consider high-energy blast sounds.

In this study, tests were conducted to investigate the behavior of absorbing materials close to explosions. The results were used to develop a new abatement measure for shooting ranges that also is given in this paper.

2 Layered absorber

2.1 Test plan

The basic idea of the test plan was to compare the signals of a blast that propagates without any interaction to the signals of the sound that propagates through the absorber. Both paths have the same geometry so that other propagation effects like absorption in air and, in particular, unknown non-linear effects can be assumed to influence both sounds in the same way. In order to measure the effect of absorbing layers, a kind of ‘tube’ was used. This tube was made of piled rings of concrete filled with the absorbing material under test

Figure 1 indicates the basic plan including the dimensions. The microphones Mp1 to Mp3 were piezo-resistive microphones; the microphone Mp4 was a 1/8” membrane microphone. The microphone membranes and sensors respectively were orientated for grazing incidence.

This paper reports on tests using the demolition simulator DM54 as the blast source. This device contains a charge that is approximately equivalent to 50 g of TNT and is easily fired by an electric impulse that is also used as the trigger for the acoustical measurements. Figure 2 shows a picture of the test site with a DM54 hanging over the center of the tube ready to fire.

In the DM54, the charge is packed between soft materials but there is also a solid plastic cap. Normally, this charge provides a spherical blast source. Sometimes however, the plastic cap can produce a sonic boom that is picked up by the microphones and may disturb the clear blast shape pressure time history. In general, with this device the acoustical source strength is reproduced within a few tenths of a decibel and, thus, this device is a reliable source for repetitive blast experiments. The most important influence on the blast strength is the temperature of the charge. This temperature should be kept constant if the absolute blast level is of importance to the experiment. This test plan did not need to record these parameters because the results of this experiment depend only on the direct comparison between sound propagating on two different paths from the same shot.

According to a simple blast model /2/, this charge has a Weber-radius of approximately 1 m. (The Weber-radius estimates the size of the sphere where the expanding gases from the demolition become subsonic.) Therefore, the first microphone was located at 1.5 m distance in order to get ‘acoustical’ pressures.

The following figures always show the time histories of the pressure at all four microphones in the same matrix of charts. The upper left time histories report the signals at Mp3. The upper right graphs show the signals at Mp1. The lower left time histories report the signals at Mp4. The lower right graphs show the signals at Mp2. The time scaling for all time histories is always the same (35 ms full scale). A common trigger, the firing impulse for the DM54 device, links the time scales to each other. However, the pressure scale is different for each signal. The positive peak pressure of the signal determines the specific maximum scale to allow a direct comparison of the shapes of the signals. For the sake of simplicity, the axes are not labeled; instead, the positive peak pressure in decibels re. 20 µPa is indicated.

The pressure signals were recorded to a digital multi-channel tape. The bandwidth was 0 Hz to 16 kHz. The piezo-resistive microphones and the 1/8" microphone were calibrated using a standard calibrator at 124 dB re. 20 µPa at a frequency of 250 Hz. The influence of limitations of the measuring chain on the time waveforms is discussed later.

Note 1: It should be mentioned here that it is somewhat of a challenge for any linear measuring system to measure reliable data at 10^4 Pa when calibrated at 31.6 Pa.

Note 2: The peak levels measured by the two microphones close to the source were originally published as different values in a prior analysis /4/. There is evidence that the published levels for the microphone measurements at Mp1 were 3 dB too high. This error is corrected in the figures given here.

Note 3: The shape of the time signal waveforms recorded by the 1/8" microphone at Mp4 is always different from waveforms recorded by the piezo-resistive microphones. There is a strong shift to negative pressures after the first positive peak pressure. The reason for this error is a temporal shift generated by the preamplifier of that microphone. This behavior previously has been observed with several devices of the same type when the measuring similarly high. Comparison of the waveform recorded by this type of microphone to the waveforms recorded by piezo-resistive microphones at the same position show that the low frequency spectrum is strongly distorted by this effect and should not be used for any spectral analysis or evaluation. The results obtained for the higher frequency ranges, however, are reliable. The negatively going pressure shift that is caused by the preamplifier recovers exponentially to zero.

This paper shows the results of five tests with explosions. The first test explosion was conducted over the grassy ground of the test site under free field conditions. The second test explosion introduced the concrete tube measured empty with the same geometry. For the next two tests, the tube was filled with different layers of absorbing materials. The last test was a measurement where a simple layer of compressed straw was piled directly on the ground without any tube at all.

2.2 Tests without absorbing materials

Figure 3 shows the results of the test without any absorber or obstacle under free field conditions. The signals at Mp1 and Mp2 should correspond to each other due to the geometry of the test plan. For linear sources, the geometric divergence evaluates to 7.4 dB, which compares to the measured difference between Mp3 and Mp4 (7.9 dB). Mp2, the microphone at the ground, clearly exhibits pressure doubling when one compares the peak level measured by Mp2 to the respective level measured by Mp4 or the level calculated from the signal at Mp1. This latter yields 171.1 dB – 7.4 dB + 6 dB = 169.7 dB. Obviously, the measured levels can be understood well by applying the rules of linear acoustics including the reflection phenomena at the ground surface.

Note: The decibel-calculations refer to peak levels. In general, there is no reason for peak levels like any pressure level to obey the spherical geometric spreading rule because there is no fundamental correlation between pressure and energy. The $1/r^2$ rule is valid if the rules of linear acoustics apply and, in this situation, if the area of consideration is the far field. Therefore, an important result is that non-linear effects and the near field conditions do not disturb this relation, at least for the lower frequencies.

All three piezo-resistive microphones record similar signal waveforms; they are typical blast waves, see /2/. The signal waveform recorded by the 1/8" microphone at Mp4 appears to be different as discussed above. In addition to this measuring error, the low frequency, negative peak pressure of the blast signal measured by Mp4 is too low even if the waveform shift is taken into account. Calculations show that the droop (phase shift) due to the high cut-off frequency for low frequencies inherent in this type of microphone fully explains this result. Considering the shape of time histories of a low frequency blast, the low-frequency bandwidth of the whole measuring chain always has such an influence. In this study, the signal waveforms of Mp1, Mp2 and Mp3 are more reliable with respect to the true shape of the blast signal. Nevertheless, even their waveforms indicate peak levels that are too low due to the high pass filters inherent in the analyzing chain. For very high energy blasts, this effect is even more important and is observed in many figures in literature that discuss the waveform of low-frequency-high energy blast waves.

Figure 4 indicates the dimensions of the concrete tube made of four rings with a height of 0,5 m each. Figure 2 shows a photograph of the site during these tests. The measured signals for the empty tube, see figure 5 at Mp1 and Mp2 clearly indicate the presence of the tube. There is the reflection (or rather scattering) at the first ring directly behind the first peak at Mp1. This reflection is rather sharp due to the missing low frequencies that are less scattered by the ring because the size of this 'reflector' is small compared to the low-frequency wavelengths. The ground reflection at Mp1 is delayed by 10.8 ms. Both signals at Mp1 and Mp2 show multiple reflections that can be explained by reflections or back-scatter from the inner surfaces and joins of the tube rings. The peak level at Mp2 is higher due to the missing geometrical spreading for the propagation in the tube towards the ground and back. Again, it is rather surprising how reliable the rules of geometric spreading apply for the peak level measured at the ground. In contrast the ground reflection recorded at Mp1 is 6 dB lower then expected. It should be noted here that this reduction is not necessarily due to absorption. The discussion here is focused on peak level that could be strongly disturbed by the superposition of scattered signals elsewhere at inner surface of the concrete tube.

2.3 Tests with absorbing materials

Figures 6 to 9 refer to two tests with absorbing layers piled in the tube. Obviously, in both cases the blast is highly absorbed by the layers. At Mp2 the levels are down by more than 20 dB compared to the test without absorbers. Also the signal at Mp1 shows no contribution that can be identified as the ground reflection at this resolution of the pressure scale. Therefore the absorbing efficiency of the piled layers is sufficient for many applications. Instead, the reflection from the surface of the 'first' absorbing layer, i.e. the one that faces the source, comes into play.

The first layer is an important feature for the benefit of such an absorber. From a general point of view, this layer must stand the direct heat and gas flow from the demolition. Therefore, for these tests it is made of steel wool, a material that provides a high heat conduction and can ‘cool’ the gases that penetrate it. From an ideal acoustical point of view, this layer should not reflect the blast wave. This criterion should hold, of course, for each following layer of absorbing material. For the first layout, the reflection of the first layer is only 7 dB lower than the peak level of the incident sound. And, upon closer examination of the waveform of this reflection, it is clear that the low frequency components are reflected. As a conclusion, the absorption works sufficiently, however, the first reflection will strongly reduce the benefit of such an absorber.

The goal of the second layout was not to improve the absorption of the blast but to diminish this first reflection. The idea was to start with a layer of steel wool with a rather low fraction of wool with thick fibers and decrease the fiber thickness from layer to layer. Therefore, the major difference between the two steps in figures 6 and 8 and figures 7 and 9, respectively, is that the first layer in the second case now provides a low density of thick fibers. In other words, the layers in the second case provide a smoother transition of the impedance from air into the absorber. The benefit of this measure is approximately 2 decibels for the first reflection in terms of the peak level. Comparing the waveforms, one can note that the low frequencies are no longer clearly present in the reflected signal; the lower frequencies seem to respond more efficiently to the measure of impedance matching. However, the reflection at the first layer remains an important criterion. In conclusion, the comparison of this result to the result of the ground reflection of the empty tube yields a reduction of approximately 4 dB in the peak level.

2.4 A very simple layout

The last test with demolitions was on a very simple absorber, just a layer of compressed straw lying on grassy ground, see figure 10. A thin layer of plastic covered the straw to protect it from rain. Figure 11 shows the set-up of this measurement and figure 12 indicates the measuring results. If one also considers the pressure doubling due to the ground reflection, then the peak pressure measured at microphone Mp2 indicated a large reduction of approximately 12 dB compared with the peak level measured at Mp2, see figure 12. As a conclusion, straw is an effective absorbing material. However in this case, the reflecting signals at Mp1 or Mp2 are of more interest because the reflection determines the benefit of such a measure.

In the recorded signal from Mp1, the reflection at the straw-air surface produces the first peak after the direct blast. The subsequent second peak results from reflection at the ground after passing twice through the straw layer. The peak levels of the reflection at the straw-air surface and the reflection at the ground are similar. However, although the amplitude resolution in figure. 12 is limited, there is evidence that the reflection at the straw-air surface layer includes more high frequencies than does the reflection at the ground. As a consequence, reflections at the straw-air surface are less important that one might believe at far distances. This occurs because the higher frequencies that make up this reflection are more attenuated by air absorption with increased travel to far distances. The plastic layer is not assumed to affect the results. It was only included in the test for practical reasons. The use of straw seems to be a very inexpensive measure with no concomitant problems with respect to the environment.

2.5 Conclusion

The reflection at the first layer has a strong influence on the benefit of the absorber. In practice, this feature is the limiting condition for any absorber that’s purpose is to reduce reflections of blasts close to the source. (Note: This criterion comes into play at any distance and for any source, of course, but for random incidence and random noise it is normally not that important). The tested layout of piled absorbing layers is, for sure, not an optimal set-up. More fundamental research is necessary to understand the interaction of high-energy impulse sounds with complex impedance surfaces. If the ground is the reflecting surface to be silenced, then there are a lot of options to the absorber layout in order to maximize absorbing efficiency.

The following investigation on a so-called ‘Multiple Screen Absorber’ is a consequence of this major conclusion from the tests. The MSA overcomes the “first-reflection” limit by forcing the sound to reflect at multiple surfaces before the sound propagates into noise sensitive areas.

3 Multiple screen absorber

3.1 Application and purpose

Noise abatement measures at rifle ranges strongly depend on the design of the range. Ramparts, walls and other constructions normally shield the muzzle blast and the projectile sound so that these sounds cannot leave the facility along a direct path into the community. In Germany - in particular at military training facilities - a sequence of safety baffles guarantees that no projectile can escape the range or, if it does, then it must follow a steep trajectory that is safe. From an acoustical point of view, these baffles are large reflectors for both the muzzle blast and the sonic boom from the projectile. The reflections from the baffles especially affect the area to the rear of the rifle range and determine the received levels for assessing the range noise in those areas.

Note: Effective measures that reduce receiver levels everywhere around the firing range are well known. For example, a 'coffered ceiling' covering the whole range yields 15 dB of mitigation /3/ without needing artificial ventilation or lights. However, such an abatement measure is rather expansive. In addition, normally residential areas do not surround a range. Most residential areas in the vicinity of a range are located to the rear of the facility with respect to the shooting direction.

As a typical example, figure 13 shows the time history for the *fast*, A-weighted level at a distance of 400 m to the rear of a military rifle range. The reflected signal levels from the baffles are significantly higher than the direct signal levels because of the acoustical directivity pattern of the muzzle blast of typical rifles: Source levels are typically 10 to 15 dB higher in the shooting direction than to the rear. Therefore, it is promising with respect to both noise reduction and costs to focus on the attenuation of the sound reflection at the baffles.

3.2 Test plan

In general, the sound propagation on an existing range is rather complex due to all of the reflecting objects including walls and baffles in front and behind the shooter. Therefore, a dedicated test site was setup to study the basic interaction of the blast sounds and the baffles. In order to analyze all the significant signals from the baffle, the test plan required measurement of the baffle reflections on a circle around the geometric center of the baffle. The radius of the measurement circle was 12 m (see figure 14) and there were 54 receiver positions located at 6 heights (2 m, 4.5 m, 6 m, 8 m, 10 m, 12 m) and in 9 directions (0°, 22.5°, 45°, ..., 180°). The signal waveforms were recorded simultaneously at the six heights for each direction.

Even with this simple geometry there are many different reflections included in the measured waveforms. These include the direct sound, the ground reflection, the reflection of the direct sound and the ground reflection at the baffle. These include also incoherent sound scattered from the edges of the baffle from both the direct sound and the ground reflection. However, each of these sound components has a certain time window during which it appears in the waveform time history. Therefore, the prediction of the time delay for the signal under consideration defines the part of the time history that is of interest for the analysis under consideration. Note: The time window for any signal under consideration should be as long as possible to allow for the widest frequency range of analysis that is possible. The geometry of the test site and the locations of source and receivers are designed to yield time histories where signals of each sound component are separated in time from one another.

All waveform analyses reported in this paper are restricted to first order sound reflections from the baffle. By a “first order reflection,” we mean that we consider only rays that are directly reflected at the baffle and then directly received by the microphones. Second order reflections, that include an additional reflection at the ground are deleted from the time history and do not contribute to the results. The period of time, during which just the first order reflection arrives , is about 5 ms. As a consequence, the results are restricted to medium and high frequencies. For muzzle blasts of typical rifles close to the source, this restriction does not affect A-weighted levels because their spectrum is dominated by higher frequency components.

3.3 The basic idea

The goal of the abatement measure at the baffle was to reduce the level of the reflection by more than 15 dB and to save costs compared to a coffered ceiling. It was clear from the tests with the layered absorber that a simple cover with absorbing material (a layer of mineral wool for example) will not be sufficient to achieve such a high reduction. The reflection at the absorber will be the limiting criterion. The basic idea of the new design to reduce baffle reflections is rather simple: Expecting 4 dB for a single absorbing layer, it would be sufficient to have 4 of simple absorbing reflections to clearly meet the requirements.

Relying on ray acoustics, figure 15 shows a sketch of geometrical configuration that forces every ray that impinges on the baffle into 4 additional reflections. Each of these 4 reflections is on a surface that is covered with an absorbing layer. This is the 'Multiple-Screen-Absorber' (MSA). Each screen is made according to the sketch in figure 16. A 35-mm thick layer of of mineral wool on both sides of an 8-mm thick solid plate provides an absorber for each reflection. A perforated aluminum sheet on each side protects the mineral wool. Of course, this geometry and design also absorbs the projectile sound and the ground-reflected sound that impinges on it, but these effects are not considered here.

3.4 Measuring results

This noise reduction measure was very successful. Figure 17 and figure 18 show the measured time waveforms without and with an MSA-design, respectively. In both figures, the first two significant signals are the direct blast signal followed by the ground-reflected signal.

In figure 17, the next clear signals are the reflections from the baffle and from the ground. Because of the MSA, no reflected signal is clear evident in figure 18.

There were 4 steps to the development of the MSA. These were:

1. A concrete baffle with a wooden cover layer
2. A baffle with a 35 mm layer of mineral wool over the wood
3. A baffle with a perforated aluminum sheet over the mineral wool
4. The MSA

The base case condition was the bare concrete baffle. Figure 19 shows the sound levels of the reflections versus microphone height for each step of the development of the MSA design in terms of the A-weighted Peak- and SEL levels. Examining the ASEL at the 8 m measuring height, there is 0 dB reduction from the flat concrete baffle, 0.5 dB from the baffle with a wooden layer, 5 dB for an additional layer of 35 mm mineral wool, and 5 dB after adding the perforated aluminum sheet. But an MSA design with 1-m wide screens yields an ASEL reduction of 21 dB, and an MSA design with 1.35-m screens yields an ASEL reduction of 24 dB. The peak-level reductions are substantially the same as the ASEL reductions at the 4.5-m, 6-m and 10-m microphone heights. These microphones are receiving a first-order reflected signal from the flat concrete baffle. In contrast, at both the 2-m microphone and the 12-m microphone heights only second order reflections (deleted during this analysis) are measurable.

Figure 20 indicates the ASEL absorption of the MSA relative to a bare baffle. Each curve in Figure 20 is for a different source height as indicated, and each curve is a function of the horizontal angle of observation. Based on a geometrical analysis, only receiving positions in a sector ranging from 157.5° to 202.5° and at heights ranging from 4.5 to 8 m really receive a geometrical reflection from both the bare and the MSA baffle design. For all other receiver positions, the received signals originate from second order reflection or scattering. The full-absorption potential of the MSA only is realized in the receiver area described above. In this receiver area (157.5° to 202.5° and heights between 4.5 and 8 m) the MSA design reduces the ASEL by 18 dB to 22 dB. Outside of this receiving area, the ASELs still are reduced. This indicates that the MSA is absorbing scattered sound as well as reflected sound.

The 12-m measurement height is somewhat special because the point of geometric reflection from the bare baffle to this receiving height lies just above the baffle (ca. 0.25-m). However, in practice there is still a clear reflection of the blast but round about 5 dB lower in level as it would have been if the baffle would just provide a full geometrical reflection condition. In case of the MSA the comparing signal at the 12-m measuring height stems from reflection or back-scattering at the topmost screen. Therefore the level difference is reading a smaller number at each measuring angle for this height; but the design is still working.
The measured results in this study strongly depend on the baffle size and shape, on the distance to the baffle, and on the height of the source (the shooter). In typical situations, however, the MSA will always absorb significant sound for some receiving area behind the shooter.

3.5 Conclusion

A 'Multiple-Screen-Absorber' is an effective abatement measure for firing ranges if noise-sensitive residential areas are to the rear and the received sound levels are dominated by sound reflections from the baffles. In this situation, the MSA is clearly more advantageous than a coffered ceiling because of cost. Also, the MSA does not affect vision and ventilation, which can be of great importance for realistic practice on a firing range.

4 Summary

This paper presents measurements of blast wave absorption with 50 g of explosives close to the blast source. In general, all layered absorbers that were tested work adequately. These tests exhibit no evidence of any significant non-linear effects. The major problem is the first layer that faces the demolition. Reflection from that surface limits the benefit of such absorbers close to a blast source. However, there may be different designs for an absorber for the muzzle blast from large guns and demolitions that are more efficient. Improved designs will require a better understanding of the interaction between blasts and absorbing materials with respect to non-acoustical and non-linear acoustical phenomena.

A multiple screen absorber designed to attenuate the reflections from safety baffles at rifle ranges overcomes limitation of the first absorber surface. Such a design reduces the level by more than 15 dB and meets all acoustical and military requirements.

5 Acknowledgements

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6 References

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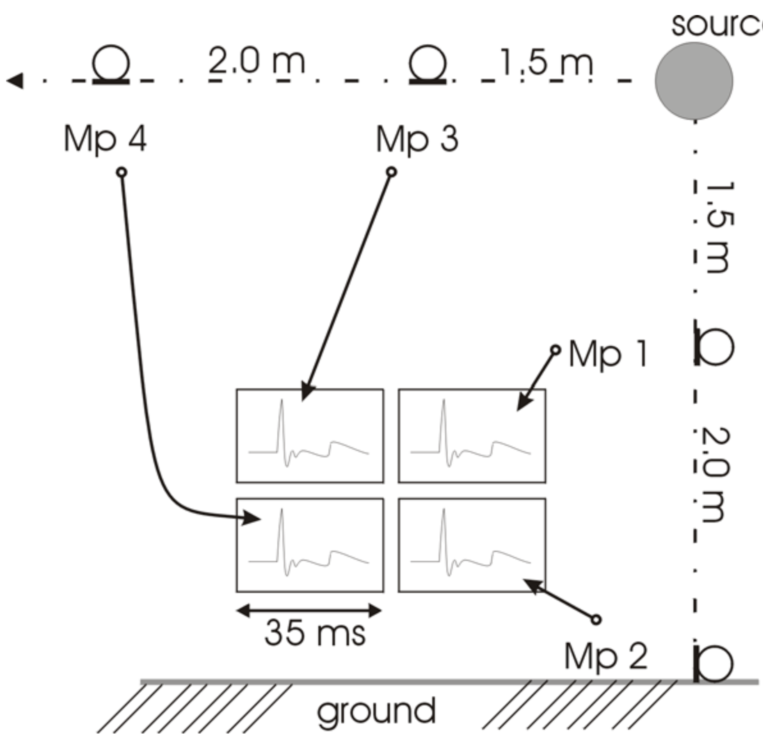

Fig. 1 Basic test plan to measure the absorption and the presentation of pressure time histories used through out this paper

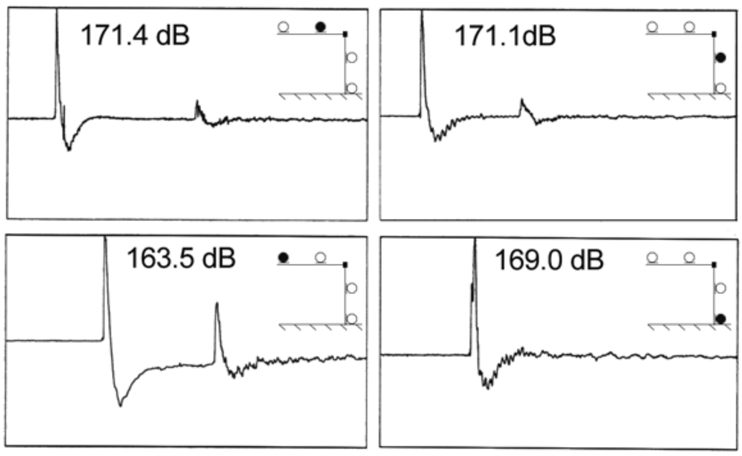

Fig. 2 Pressure time histories for the free field measurement (scaling see fig. 1)

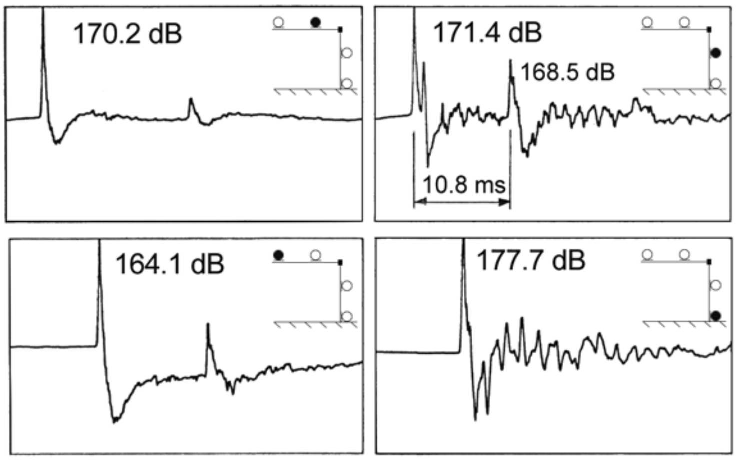

Fig. 3 Pressure time histories in the presence of the empty tube (scaling see fig. 1)

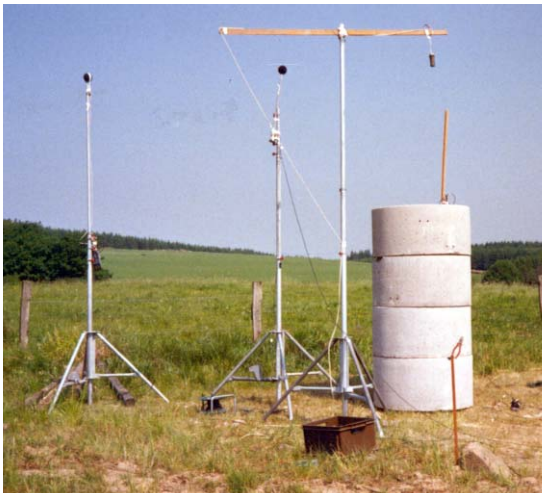

Fig. 4 The test site ready to fire
Demolition simulator DM54 located above the tube, MP3 and MP4 to the left of the source, MP1 and MP2 not visible in the centre at the top and bottom of the tube, respectively

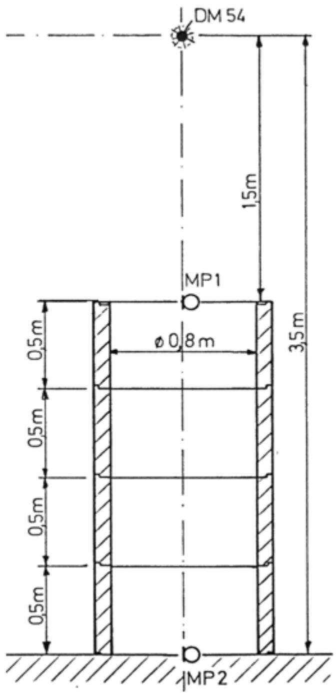

Fig 5 The empty tube including dimensions and measuring positions of MP1 and MP2

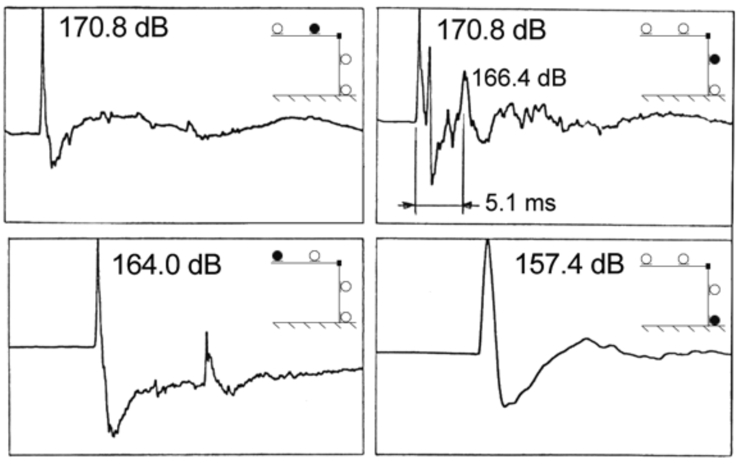

Fig. 6 Pressure time histories for the layered absorber according to fig. 8 (scaling see fig. 1)

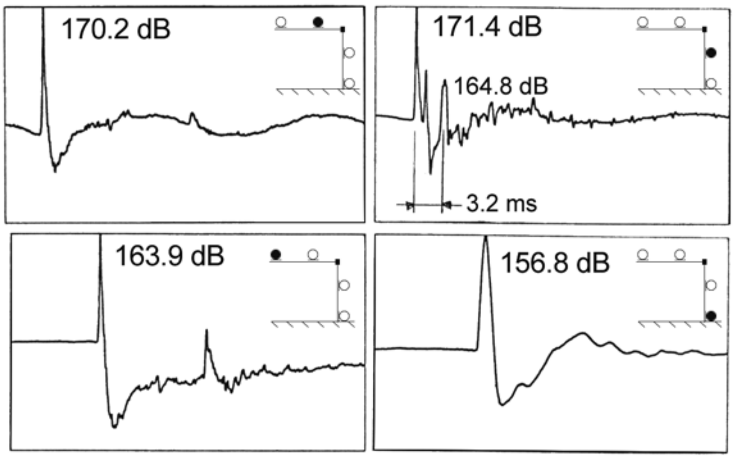

Fig. 7 Pressure time histories for the layered absorber according to fig. 9 (scaling see fig. 1)

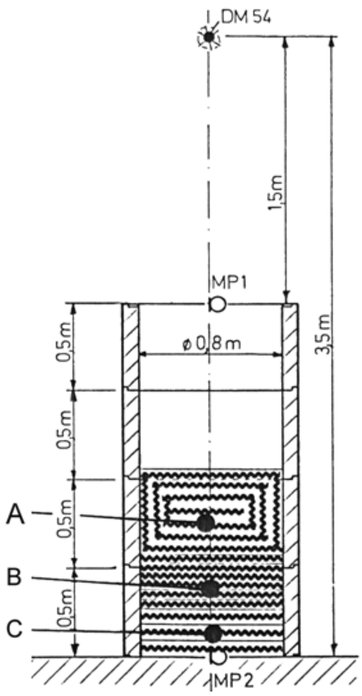

Fig. 8 Tube filled with 3 layers

A mineral wool ≈ 55 kg/m³

B mineral wool ≈ 90 kg/m³

C mineral wool ≈ 140 kg/m³

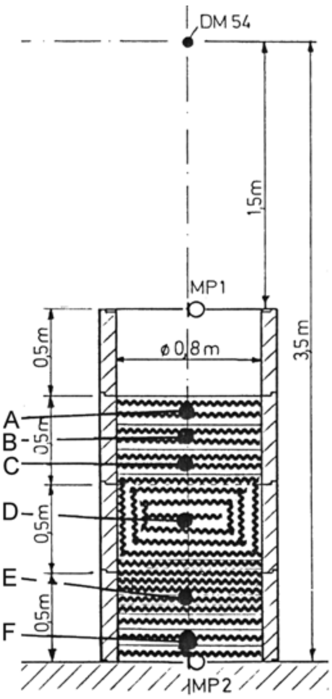

Fig. 9 Tube filled with 6 layers

A steel wool ≈ 270 kg/m³, fibres Nr. 6, thick,
B steel wool ≈ 270 kg/m³, fibres Nr. 4, medium
C steel wool ≈ 257 kg/m³, fibres Nr. 2, thin
D mineral wool ≈ 55 kg/m³
E mineral wool ≈ 90 kg/m³
F mineral wool ≈ 140 kg/m³

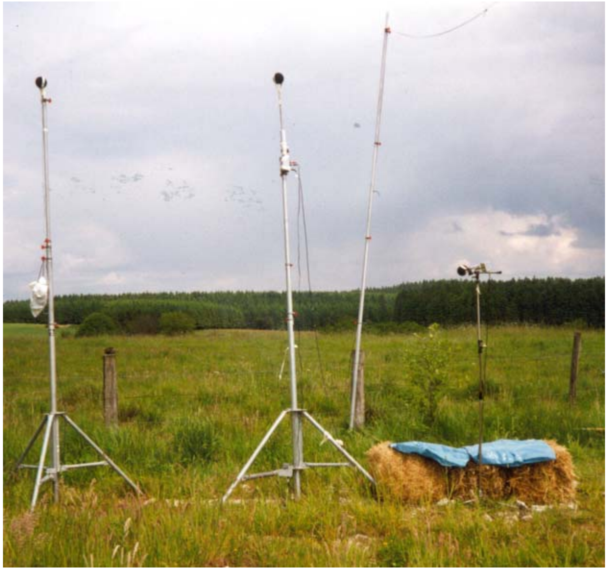

Fig. 10 Test site with straw

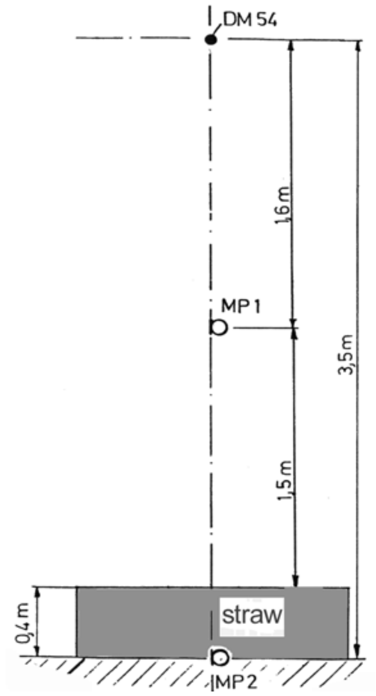

Fig. 11 Set-up for measuring the straw absorber

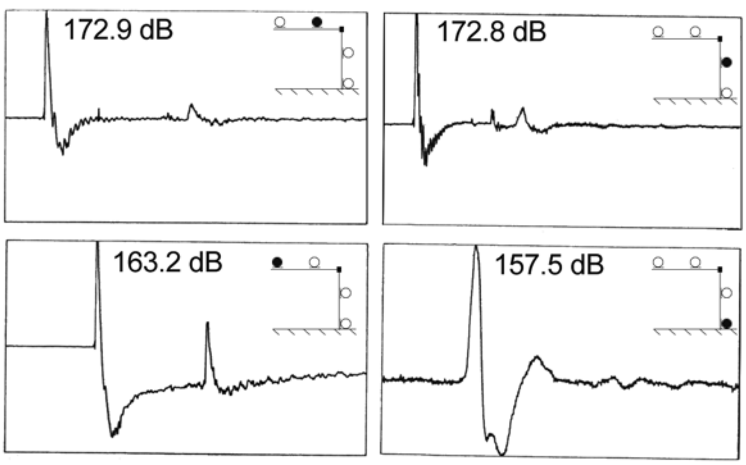

Fig 12 Pressure time histories for the compressed straw absorber, according to fig.11 (scaling see fig. 1)

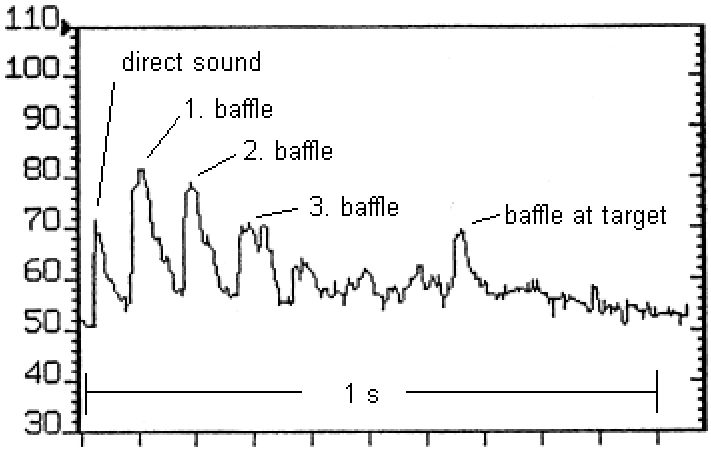

Figure 13 A-weighted level [dB] versus time received at the rear of a rifle range with baffles, distance 300 m

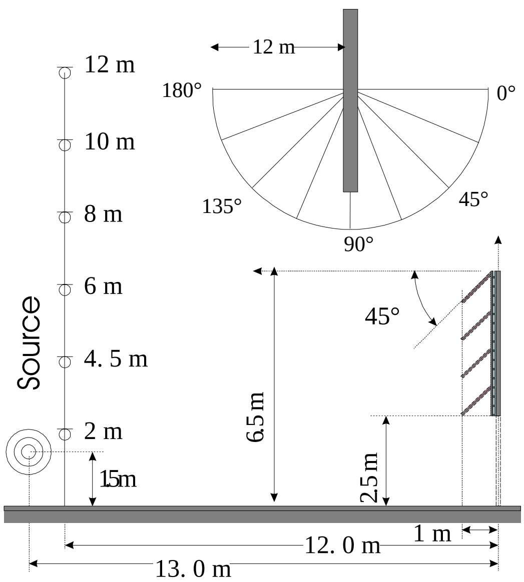

Fig. 14 Measuring layout for baffle reflection into the 180° direction at

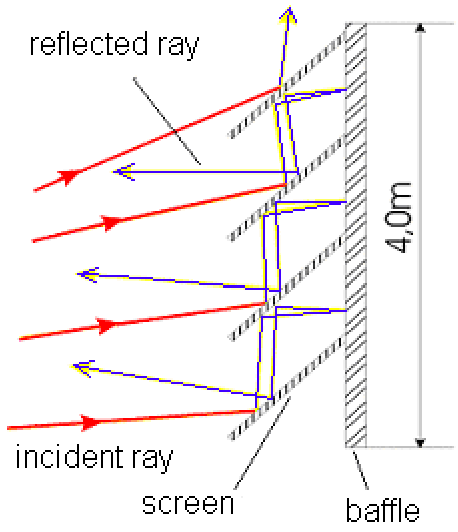

Fig. 15 Sketch of the ray tracing through a 'multiple-screen' design

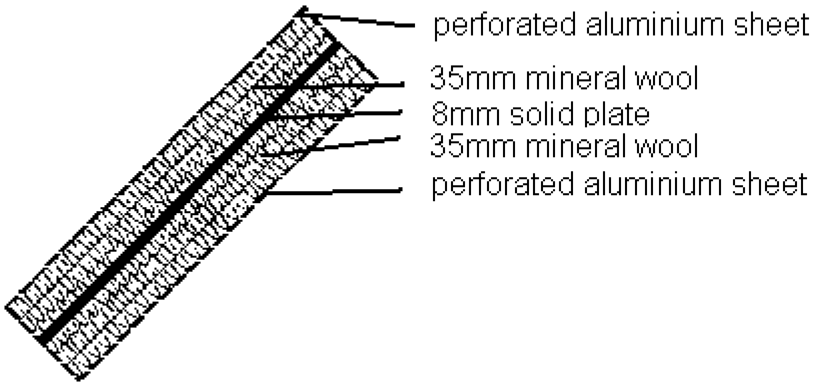

Fig. 16 Sketch of screen
Perforated aluminium sheet, holes: area 37%, diameter 6 mm
Mineral wool, 35 mm thick
Solid plate, 8 mm thick

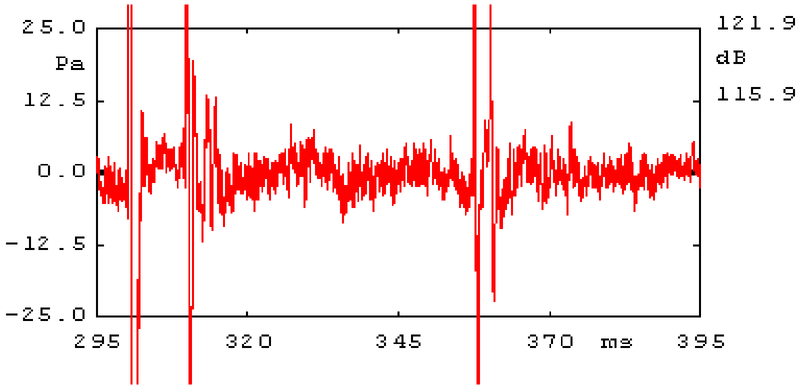

Fig. 17 Pressure time history of the signal measured at 8 m height with a baffle covered with the wooden layer

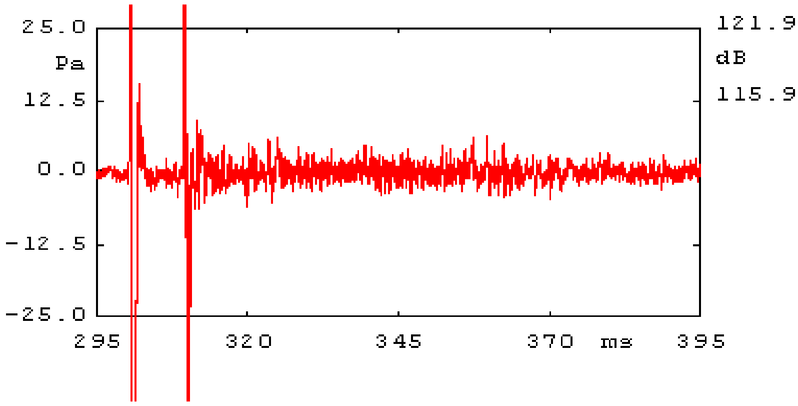

Fig. 18 Pressure time history of the signal measured at 8 m height with a Multiple-Screen-Absorber

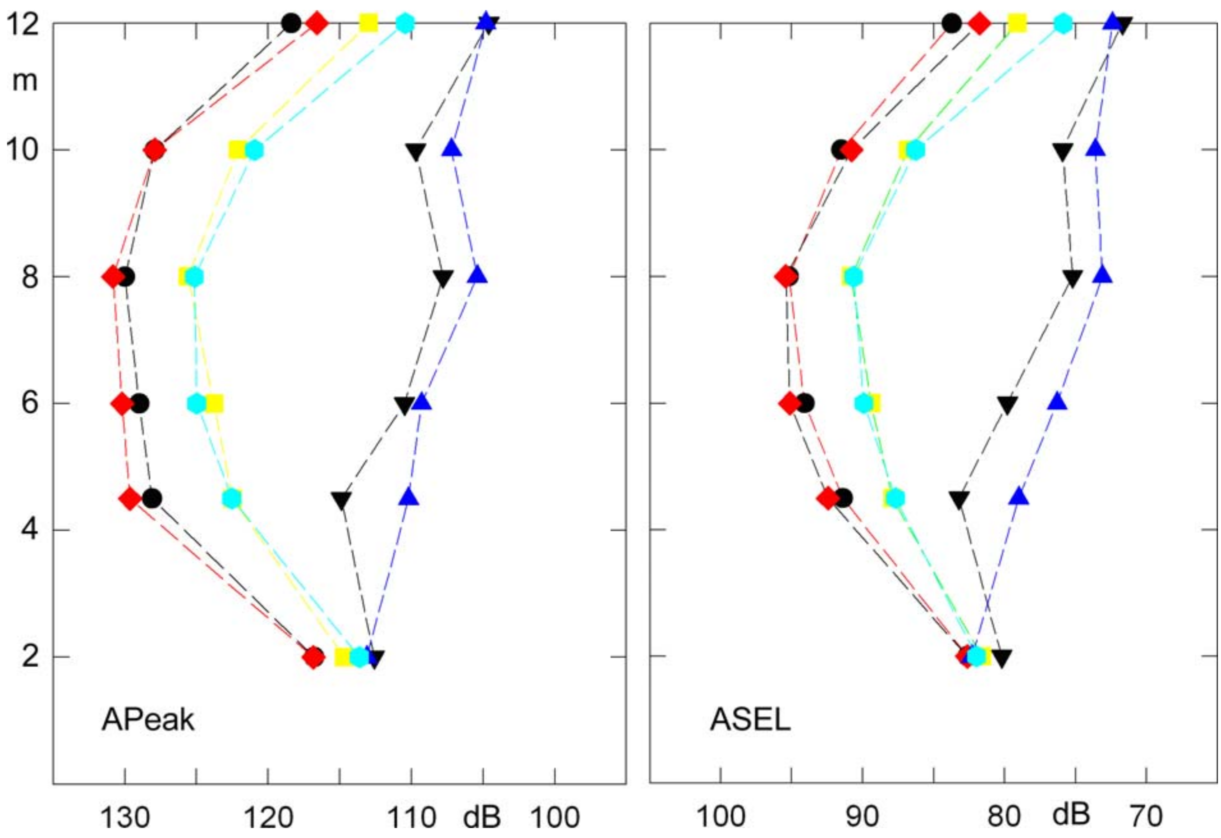

Fig. 19 A-weighted peak level (left graph) and A-weighted sound exposure level (right graph) at 6 receiver heights for the steps of developing a MSA, firing position is 13 m in front of the baffle, 1.5 m above the concrete floor of the test site

- ◆ flat concrete baffle
- ● with wooden shield
- ■ with 35 mm layer of mineral wool covering the wooden shield
- ● layer of mineral wool plus perforated aluminium sheet
- ▼ MSA design with 1-m wide screens
- ▲ MSA design with 1.35-m screens

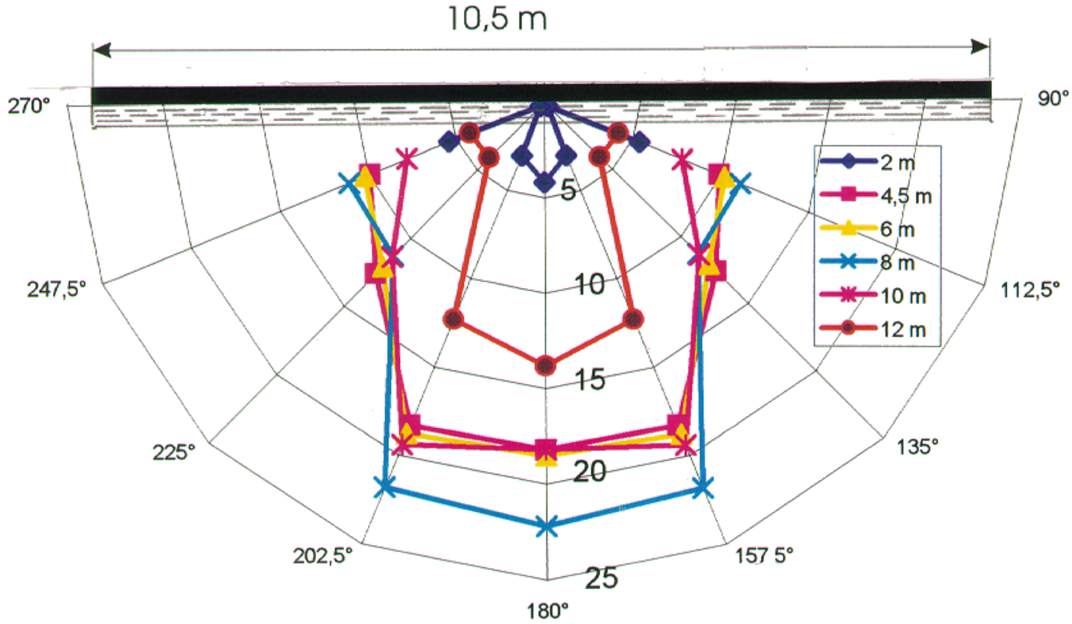

Fig. 20 Level reduction of ASEL for different measuring heights versus reflection angle. Source at 13 m centered in front of the baffle, levels measured on a 20 m radius circle around the center of the baffle