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Institut
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Noise Control

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An Overview on Military Weapon Noise: Its Physics and Annoyance

Overview

- ⇨ Introduction
- ⇨ Military weapons
- ⇨ Blast sources
- ⇨ Long range propagation
- ⇨ Reception of blast sounds
- ⇨ Human response to blasts
- ⇨ Assessment of shooting noise in Germany
- ⇨ Summary

Sound and noise

things to make clear

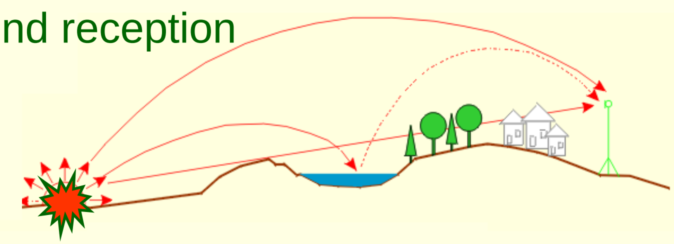
If you tell people,
that the bangs are coming from a display of fireworks they open the windows to catch a glimpse and to enjoy it.

If you tell people,
that weapons are firing, they close the windows and are upset that their windows do not stop the sound from coming in.

⇨ **However,** at the ear, the bangs of both activities cannot be distinguished in physical terms, most of the times.

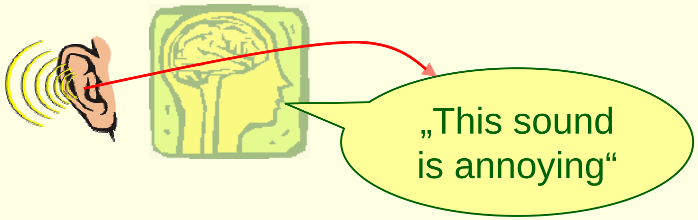
⇨ **Therefore,** the words ‚military‘ and ‚weapon‘ both belong to the human response side.

- ⇨ sound radiation
- ⇨ sound propagation
- ⇨ sound reception



physical side
sound

- ⇨ bias
- ⇨ rating
- ⇨ assessment



human response side
noise

Health warning

keep it simple but ... stay on the right side

- In acoustics, the physical side is often reduced to aspects that - ‚at the end of the day' - seems to be necessary to know for rating and assessment.
- The ISO 9613, for example, only describes the attenuation of A-weighted levels, reducing source and propagation features to audible measures. As a consequence, these procedures are not applicable to other weightings?!

We will not fall into that trap of apparent simplification.

We stay on the physical side as long as possible because high energy blasts are rather specific sounds and deserve acoustical correctness.

Status

Weapons and their sounds

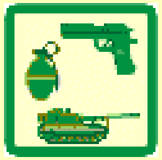
it is really a challenge ...

- **Muzzle blast**
  generated by the supersonic expanding gases of the propellant

- **Projectile sound**
  generated along the trajectory, often an impulsive report due to the supersonic speed of the projectile on parts of the trajectory

- **Explosion**
  detonation of explosives of heat ammunition at the target (or elsewhere) or detonation of grenades and bombs

WinLarm‘s module Weaponer gives an closer look into the multitude of civil and military weapons



Weaponer

Status

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  - Explosions in air
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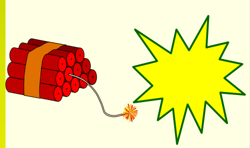
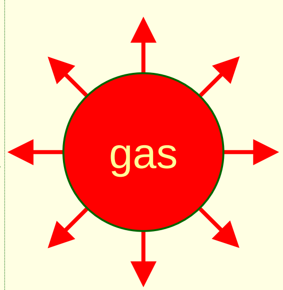
The ideal image of an explosion

reduced to the max

explosives fired, generating hot gas

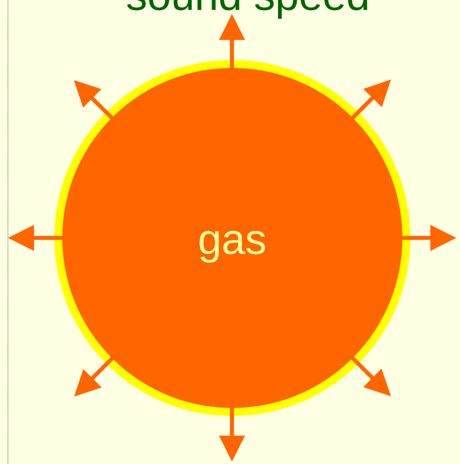


the gas bubble expands with supersonic speed, no sound radiation



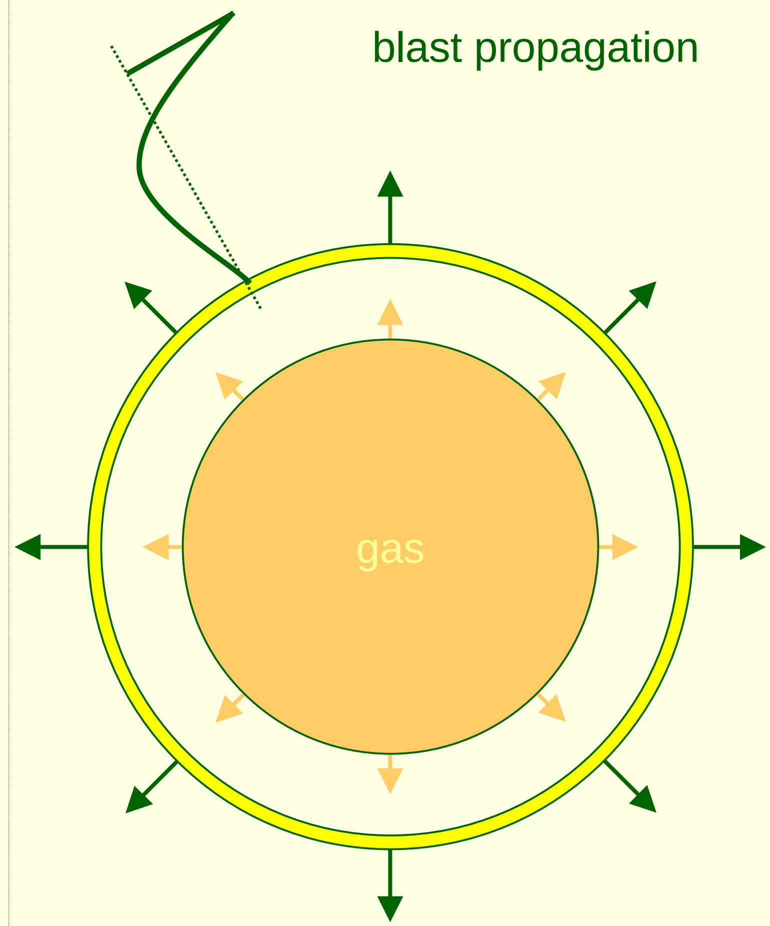
$v_{gas} >> c$

the very moment of sound radiation, gas speed equals sound speed



$v_{gas} = c$

blast propagation



$v_{gas} < c$

„An Overview on Military Weapon Noise: Its Physics and Annoyance“, Seoul National University, Korea, 2003

A simple acoustical model

Weber, 1939

The bubble is just a sphere moving in volume mode.

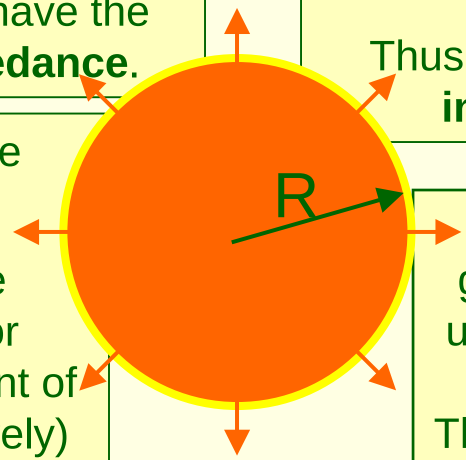
Hence, we do have the **radiation impedance**.

The speed of the gas equals the speed of sound.

Thus, we do have the **initial particle velocity**.

The geometry is given by the **radius** of the sphere.

Consequently, we only have one free parameter which for sure correlates to the amount of gas (to the energy respectively) involved in the explosion.



$v_{gas} = c$

The sound is obviously generated in the air at rest under normal condition.

Therefore, let‘s make is easy and assume an **ideal gas**.

This is all we need to calculate the Fourier-spectrum of the blast.

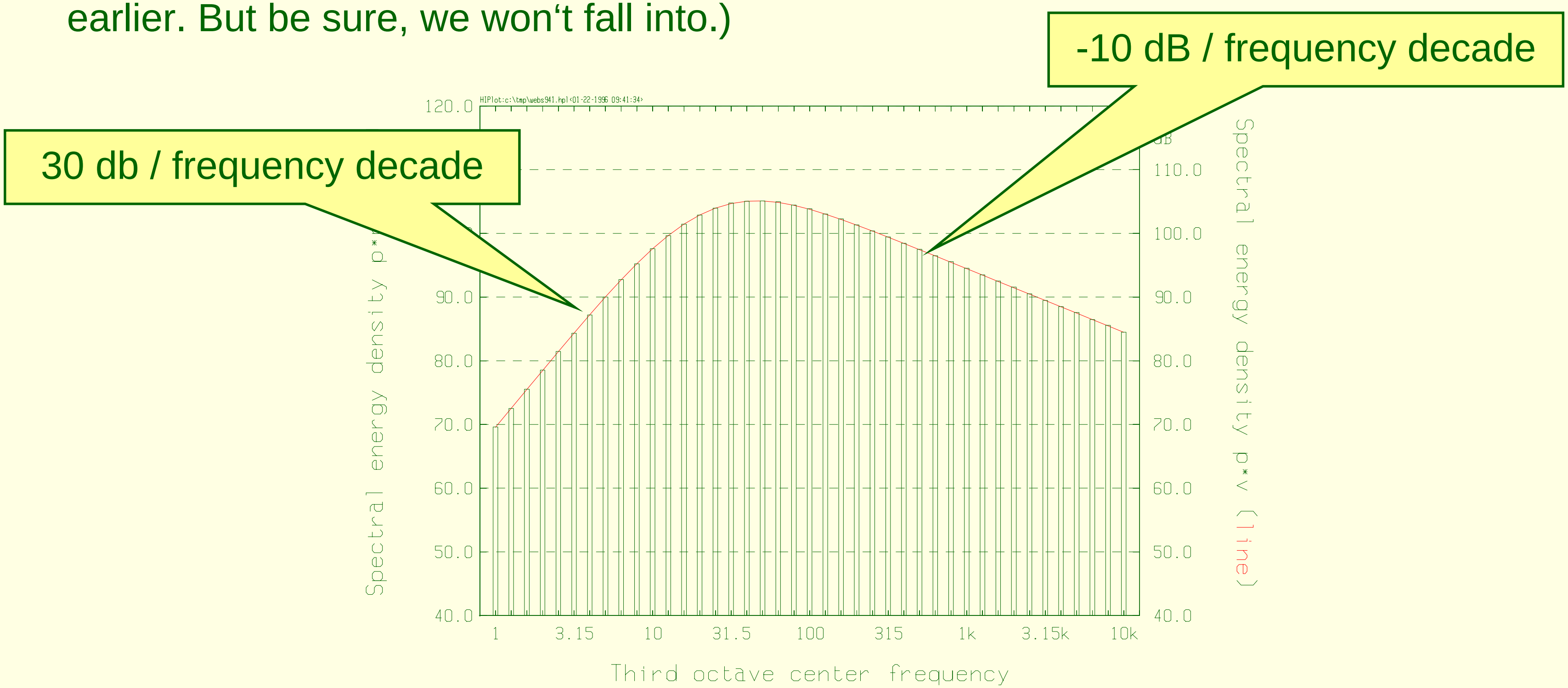
The Weber spectrum

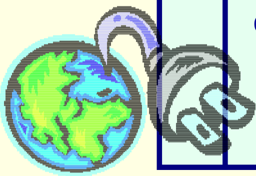
published in „Akustische Zeitschrift“ 1939

In 1939, WEBER deduced this model to describe the acoustics of spark gaps. He did all the calculations and came up with a Fourier-spectrum.

We will apply his model to explosions in air.

In acoustics, one-third octave spectra are used to indicate the sound.
(This is only half the truth and another example for the ‚trap‘ that was mentioned earlier. But be sure, we won‘t fall into.)





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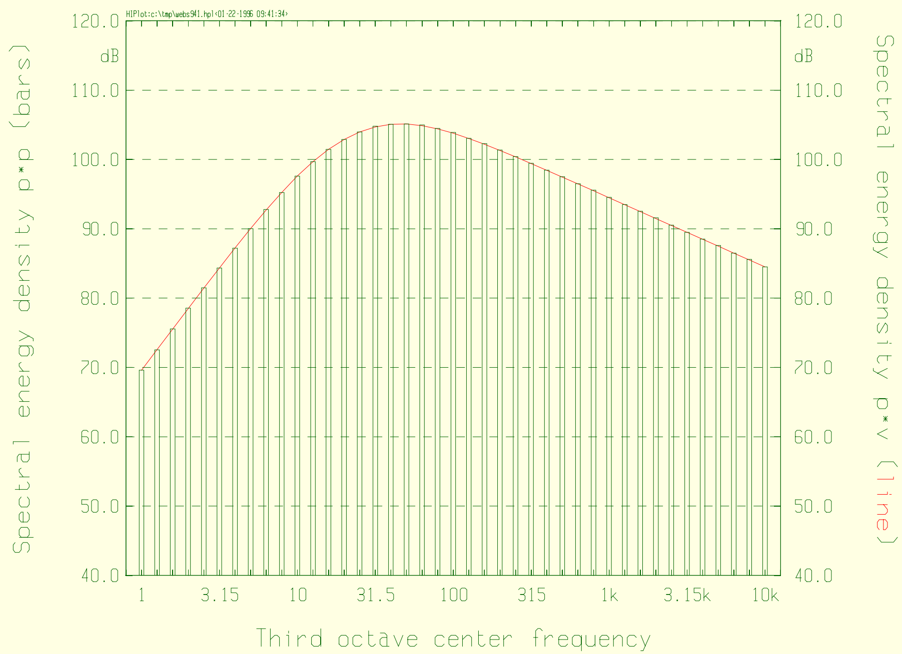
The Weber spectrum

published in „Akustische Zeitschrift“ 1939

Weber-Spectrum

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

α	$\frac{3c}{R_W}\left[1+\left(\frac{c}{\omega R_W}\right)^2\right]^{\frac{1}{2}}$
P_W	14,4 kPa
R_W	Weber-Radius
ω	Circular Frequency
c	Speed of Sound



Features of the Weber Model

not really complete

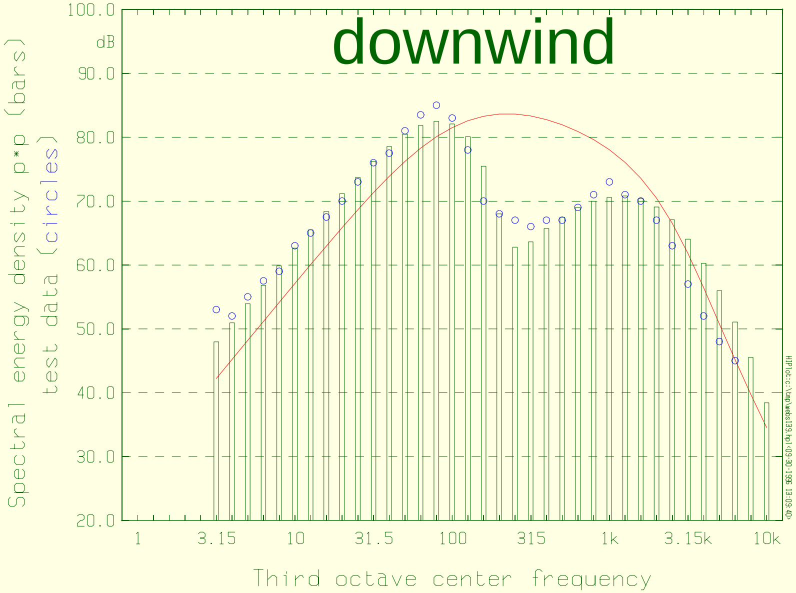
- Doubling the amount of explosives means doubling of primary energy, yields doubling of gas volume, yields increase the Weber-Radius by $\sqrt[3]{2}$.
- The particle velocity at the surface of the sphere is always c and does not depend on R and so does the acoustical pressure (Weber assumed 14,4 kPa). Therefore, the energy flow density is a constant.
- But the total acoustical energy radiated into the vicinity is the integral over the surface of the Weber-Sphere, so the intensity increases.
- At a constant distance from the source the intensity of a higher charge is greater.
- Due to the radiation impedance of a sphere the spectrum of a higher charge is shifted to lower frequencies.
- The shape of the spectrum remains the same.

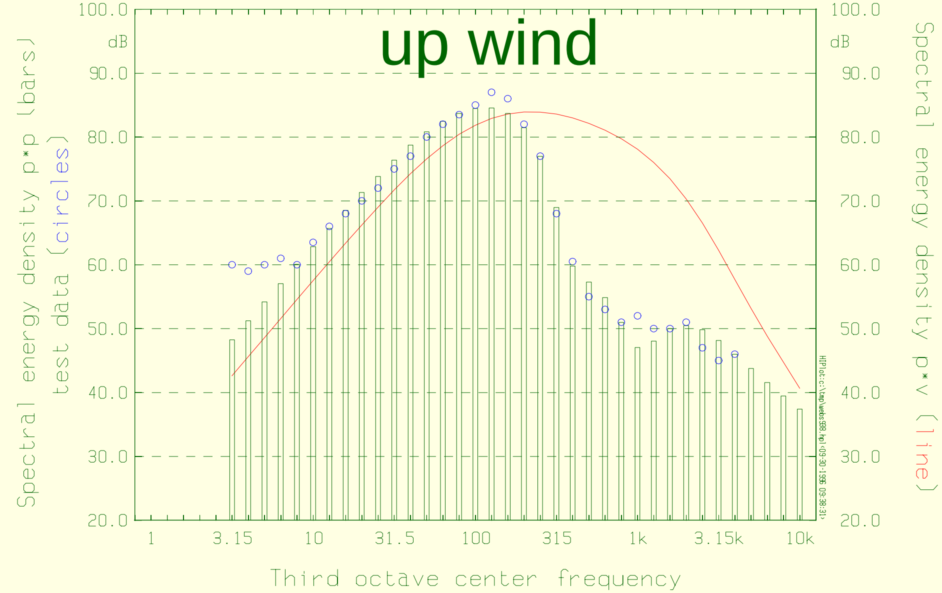
50 g TNT explosion measured at 250 m distance

not to small and not too big ...

- The blue circles indicate the received acoustical pressure square.
- Forget the bars for a moment.

- The red lines indicate the Weber-spectrum, corrected for air absorption.
  The Weber-spectrum represents the acoustical energy present at the receiver.





The measured blue circles don‘t follow the theoretical red line at all.

If we would focus, what we will not do, on A-weighted levels we would conclude:
The model overestimates the sound and predicts the same level up wind and downwind.
The model is „rubbish“!

Acoustical correctness

on male and female measures

Sound pressure cannot propagate alone:

He needs a female companion, the sound velocity.

To be politically correct and to obey gender correctness I would like to mention that in German the pressure is „**der** Druck“ and the particle velocity is „**die** Schnelle“☺

There is no conservation law for sound pressure or for sound pressure square or for intensity, only acoustical energy is preserved.

We should not fall into the trap that a so-called „energy equivalent“ level measures acoustical energy. Such levels correlate to signal energy.

You never have plane waves.
The ground reflection is significantly different for spherical waves!

In outdoor blast experiments, you never have free field conditions, because the ground is always close to source or receiver.

Acoustical correctness

consequences

- ⇨ Sound pressure is only one half of the acoustical world.
- ⇨ Therefore, microphones only measure half of the truth.
  (Sorry, that is also true for Bruel & Kjaer microphones :-)

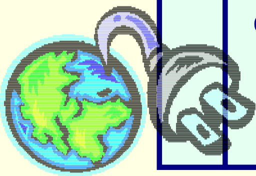
- ⇨ To get the whole world of an acoustical wave you always need two paired measures at a given location, for example

sound pressure — particle velocity

intensity — characteristic impedance

sound pressure ⊘ characteristic impedance

- ⇨ To get the whole world of an acoustical field you need to know all waves passing the receiver to understand measurements at a certain location.



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Waves at the receiver

superposition of direct and reflected wave

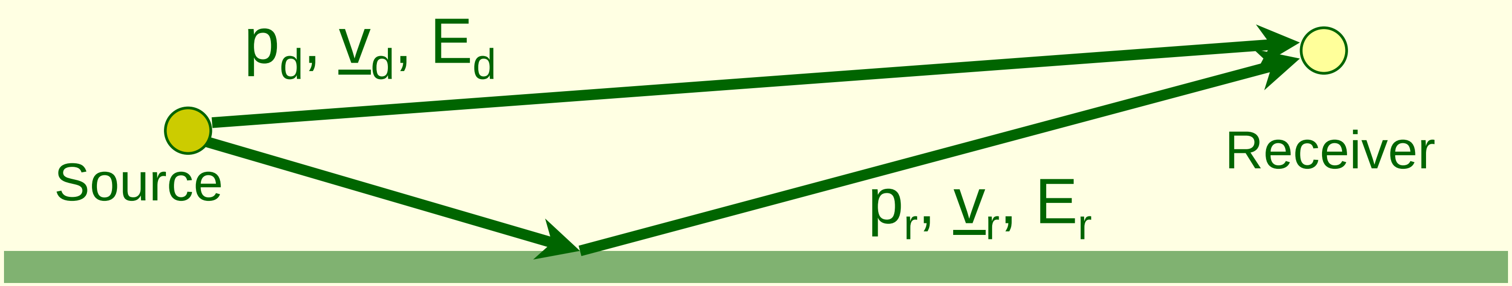
E is the energy that is present in the vicinity of the receiver

$$\textit{Energy flow density} := \frac{E}{\textit{vicinity}} = \frac{E_d + E_r}{\textit{vicinity}}$$

$$\frac{E_i}{\textit{vicinity}} = \frac{\iint\limits_{area,\,event} p_i \underline{v}_i \, d\underline{A}\, dt}{\textit{vicinity}}, \quad d\underline{A} \parallel \underline{v}_i$$

note that

$$\begin{matrix} p = p_d + p_r \\ \underline{v} = \underline{v}_d + \underline{v}_r \end{matrix} \Rightarrow \underline{I} = p\underline{v} = (p_d + p_r)(\underline{v}_d + \underline{v}_r), \quad \frac{E}{\textit{vicinity}} \neq \iint\limits_{area,\,event} \underline{I}\, d\underline{A}\, dt$$



Hirsch
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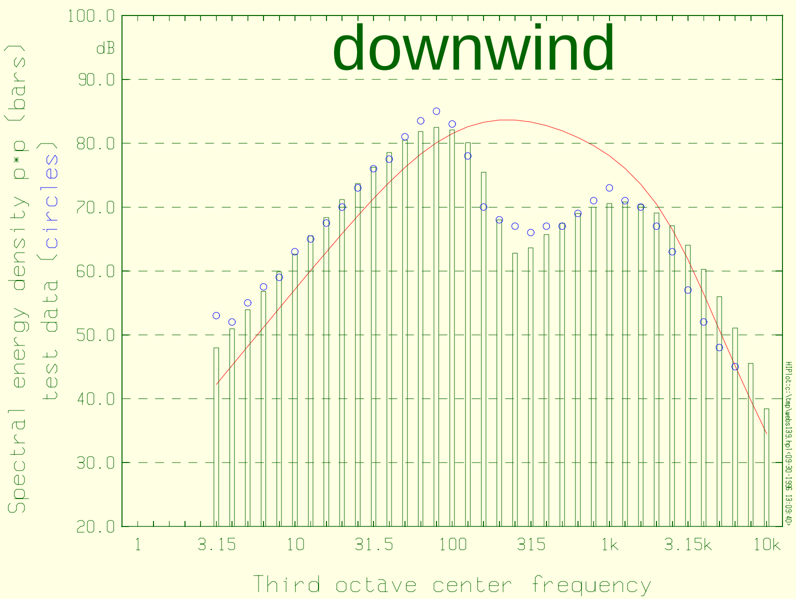
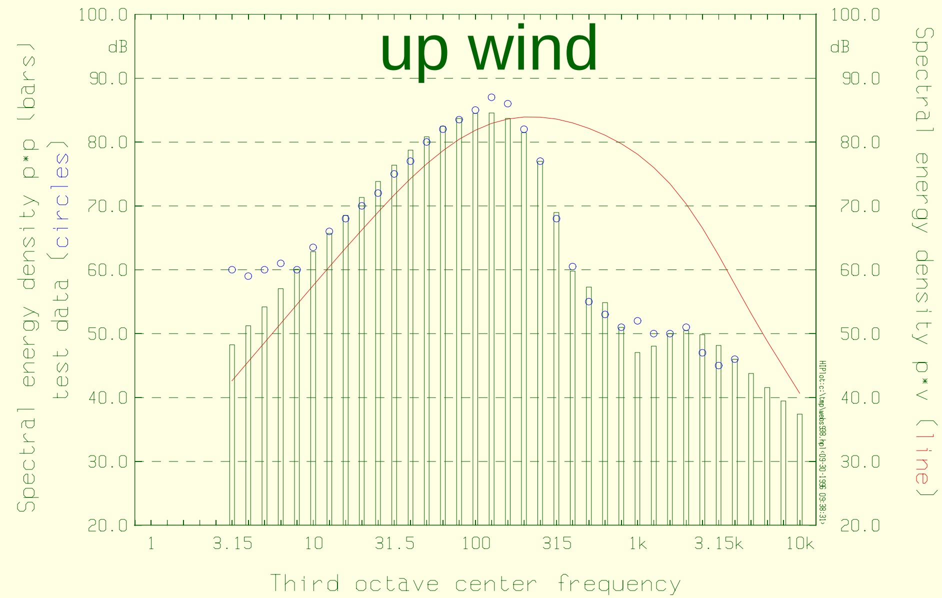
50 g TNT example measured at 250 m distance

again ...

- The blue circles indicate the received acoustical pressure square.
- The bars indicate the predicted pressure square if the superposition of direct wave and reflected wave is considered (spherical waves at complex impedance ground.)
- The red lines indicate the Weber-spectrum, corrected for air absorption. The Weber-spectrum represents the acoustical energy present at the receiver.

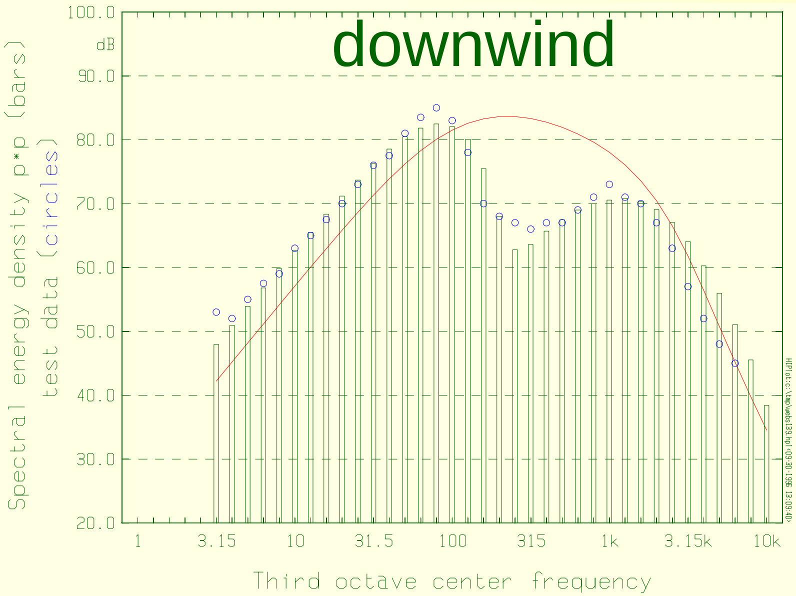


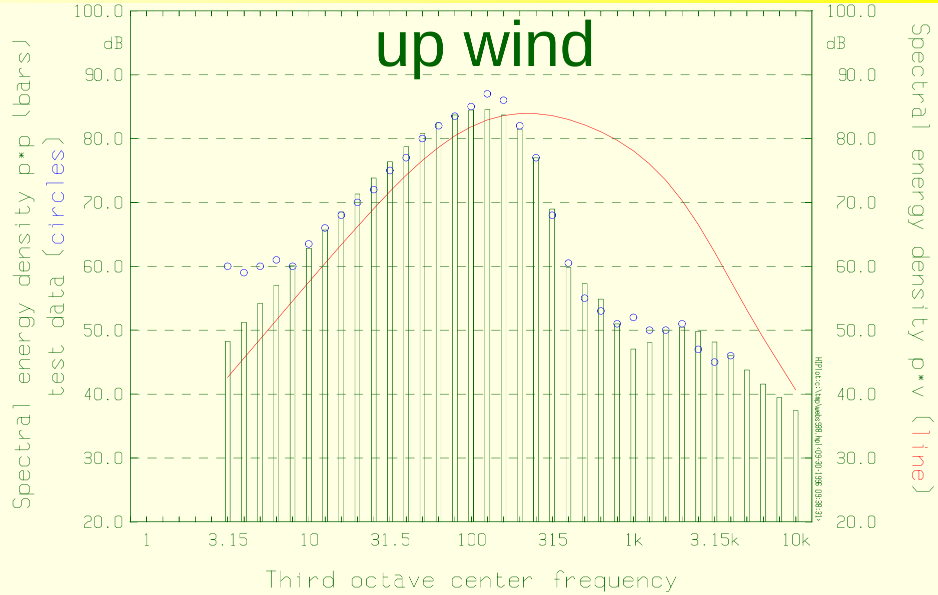


The Weber model predicts the measuring result if we are acoustically correct.

50 g TNT example measured at 250 m distance

and again ...





The ground shifts the phase of the pressure, thus there is pressure release in the audible frequency range if it comes to superposition. The energy is stored in the particle velocity, it is not gone.

The wind is considered not to curve the ray but to carry the sound with higher or lower additional speed. **The key parameter is the angle of incident of the ground reflection.**

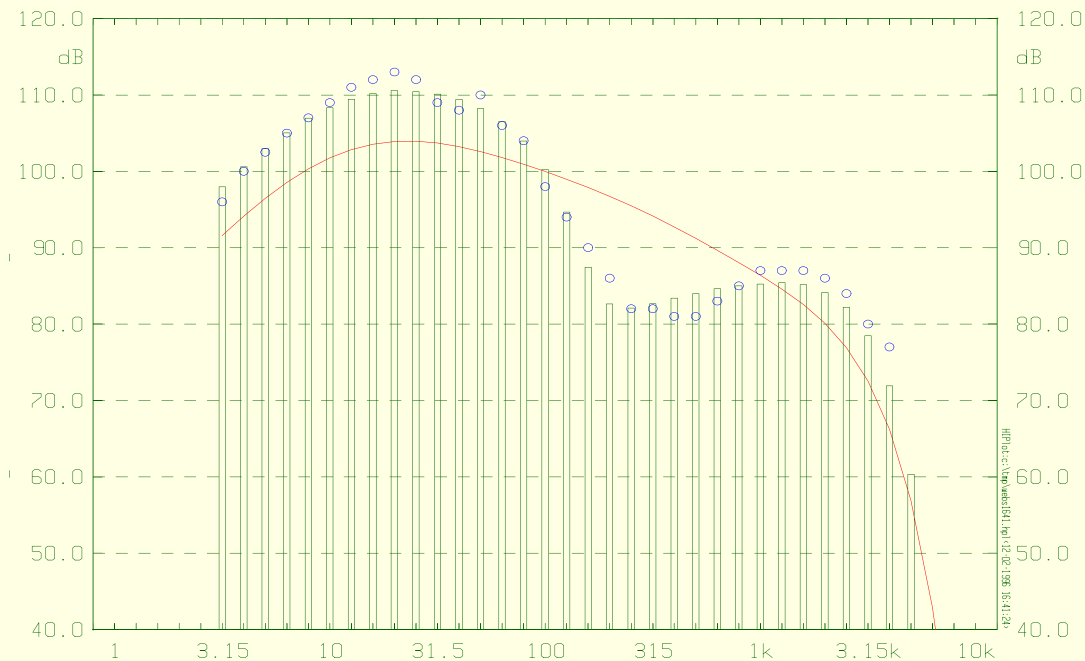
The energy present at the downwind and up wind receiver is the same, but the sound pressure is different.

If we would focus, what we will not do, on A-weighted levels we would conclude: The Weber model predicts the source spectrum but be cautious to apply ISO 9613. It may predict „rubbish“!

Weber model for a large explosion

16.5 kg TNT, 825 m distance, 1.5 m measuring height

- The blue circles indicate the received acoustical pressure square.
- The bars indicate the predicted pressure square if the superposition of direct wave and reflected wave is considered (spherical waves at complex impedance ground.)
- The red lines indicate the Weber-spectrum, corrected for air absorption. The Weber-spectrum represents the acoustical energy present at the receiver.



The simple model does not only apply to small weapons, it also is applicable to large weapons.

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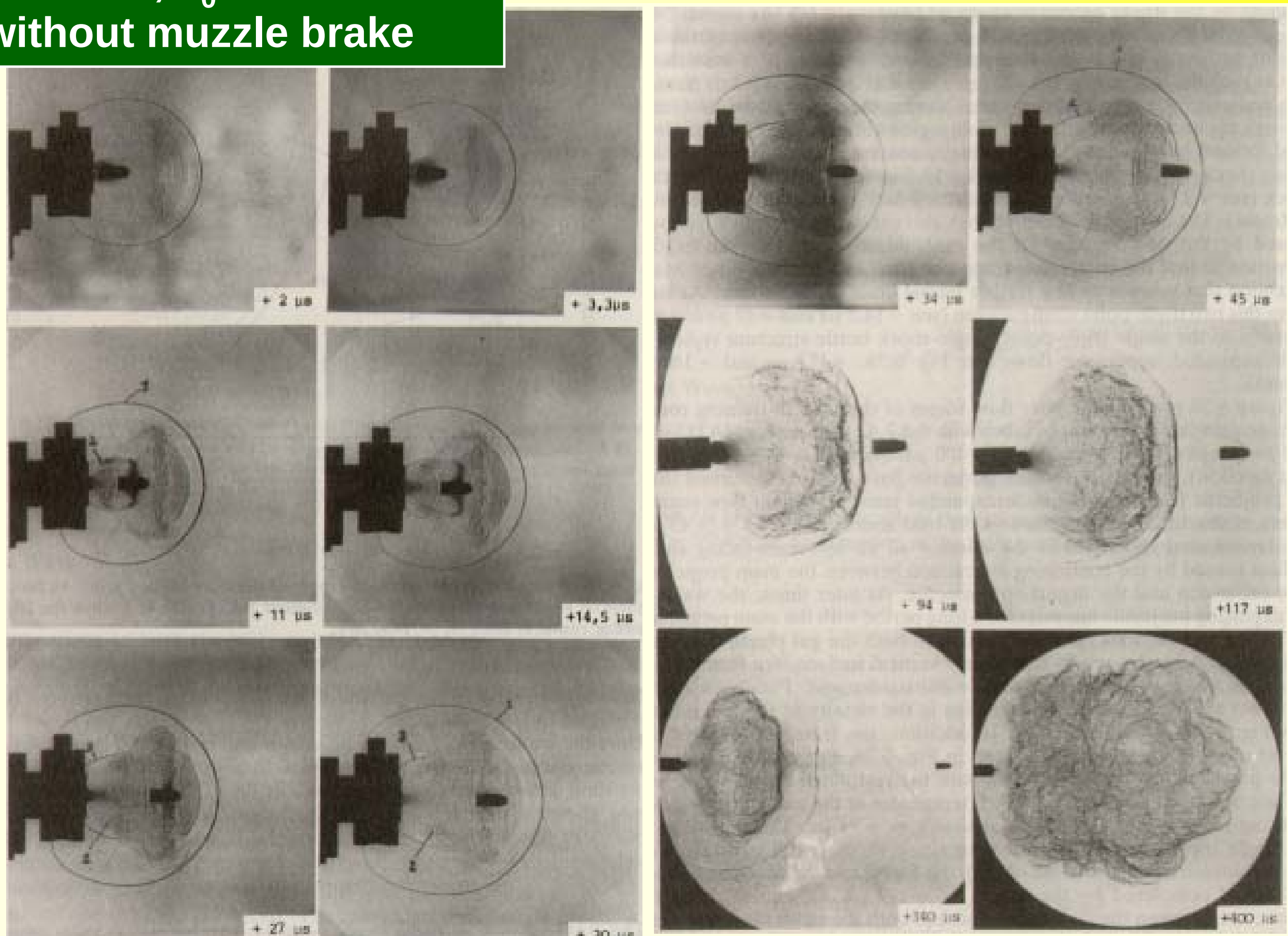
Have a close look

and keep smiling ...

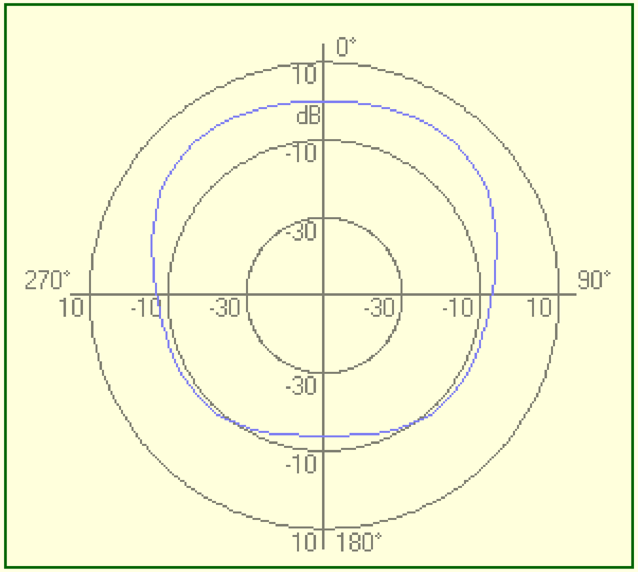
G3 muzzle blast
cal. 7.62, v_0 =780 m/s
without muzzle brake



From „Gun Muzzle Blast and Flash“, Progress in Astronautics and Aeronautics, Volume 139

Directivity pattern

105 mm cannon



- ⇨ The muzzle blast is strongly directional.
- ⇨ As a rule of thumb:
  The longer the barrel the stronger
  (assuming constant calibre).
- ⇨ Levels measured to the rear of the weapon can be 20 dB lower than levels in the direction of fire.

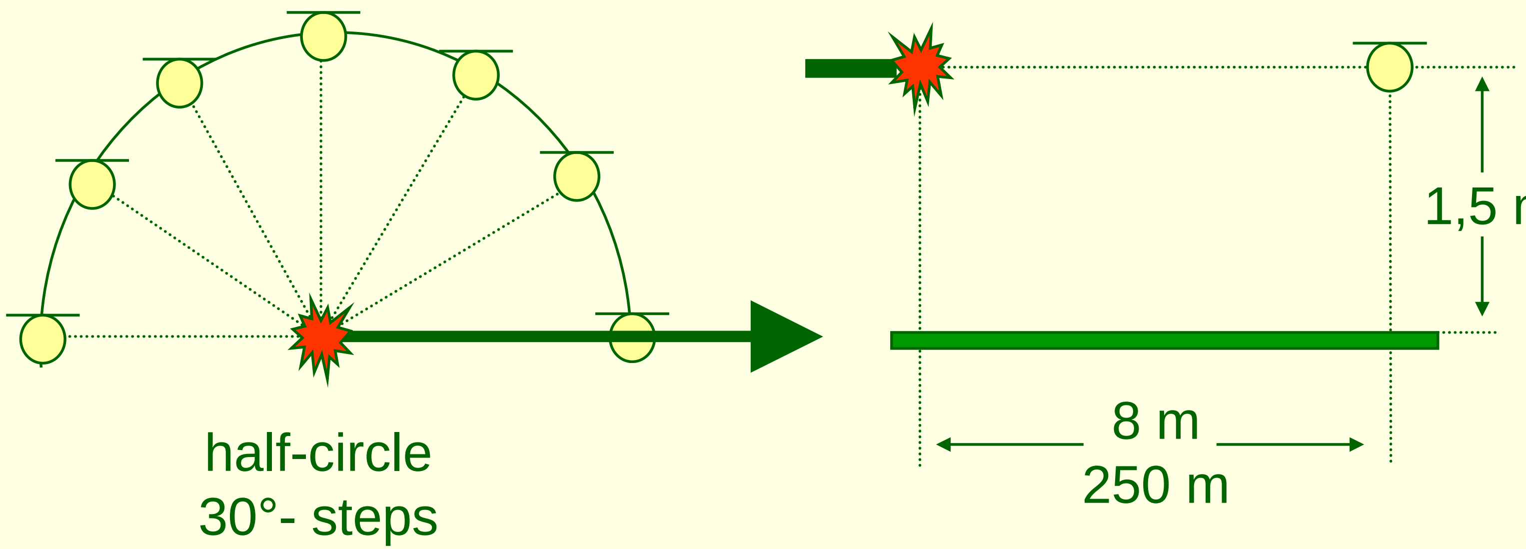
All models that predict shooting sound must carefully take into account shooting direction and the directivity pattern of the weapon under consideration.

Test plan

relying on rotational symmetry around the line of fire

Typical set-up for a source measurement:

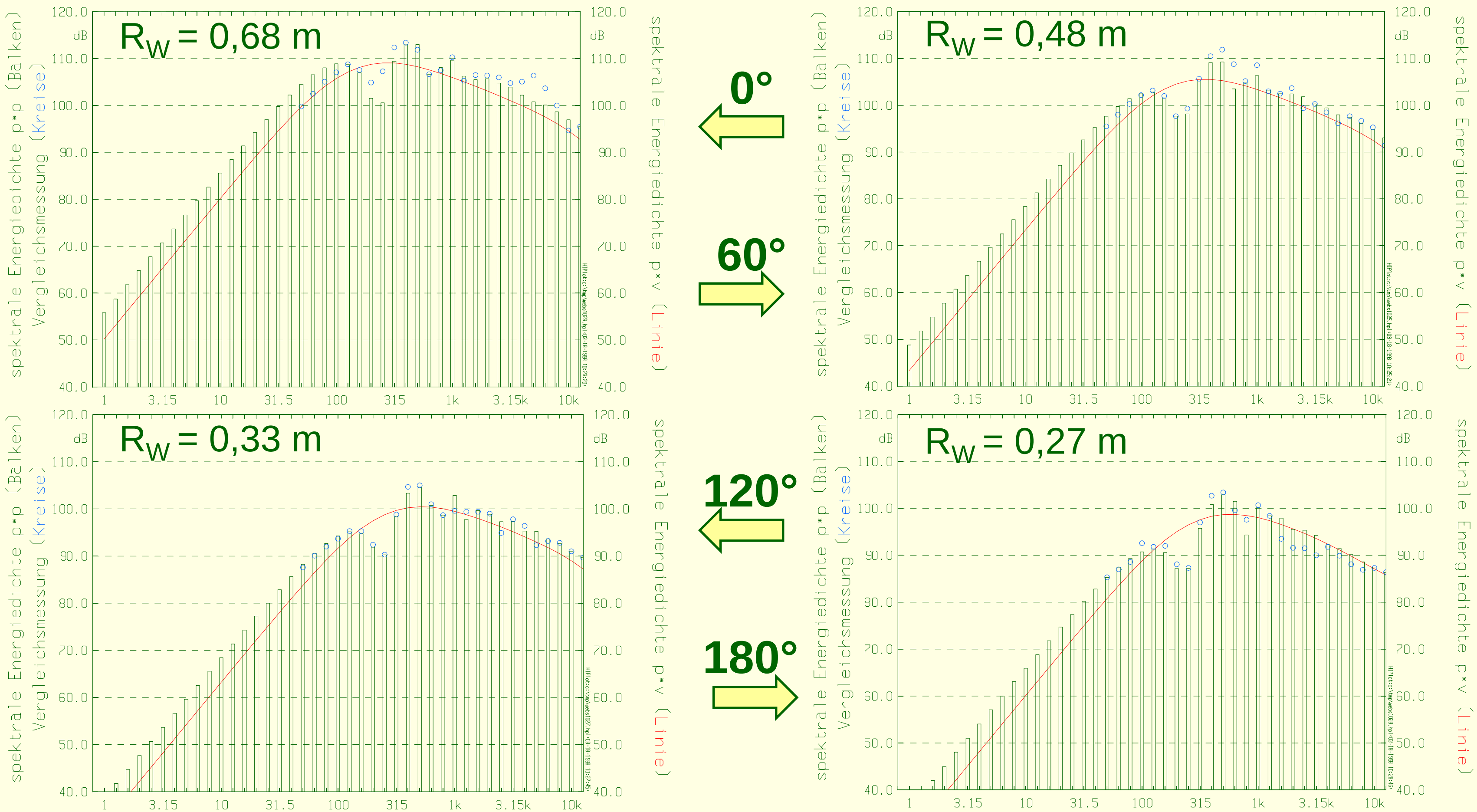
- for small arms, radius of 10 m
- for large weapons, radius of 250 m
- clear, flat, grassy ground



Weber model and directivity

it is not too bad ...

Though the gas bubble is not a sphere, it looks like a sphere of different radius from different directions.

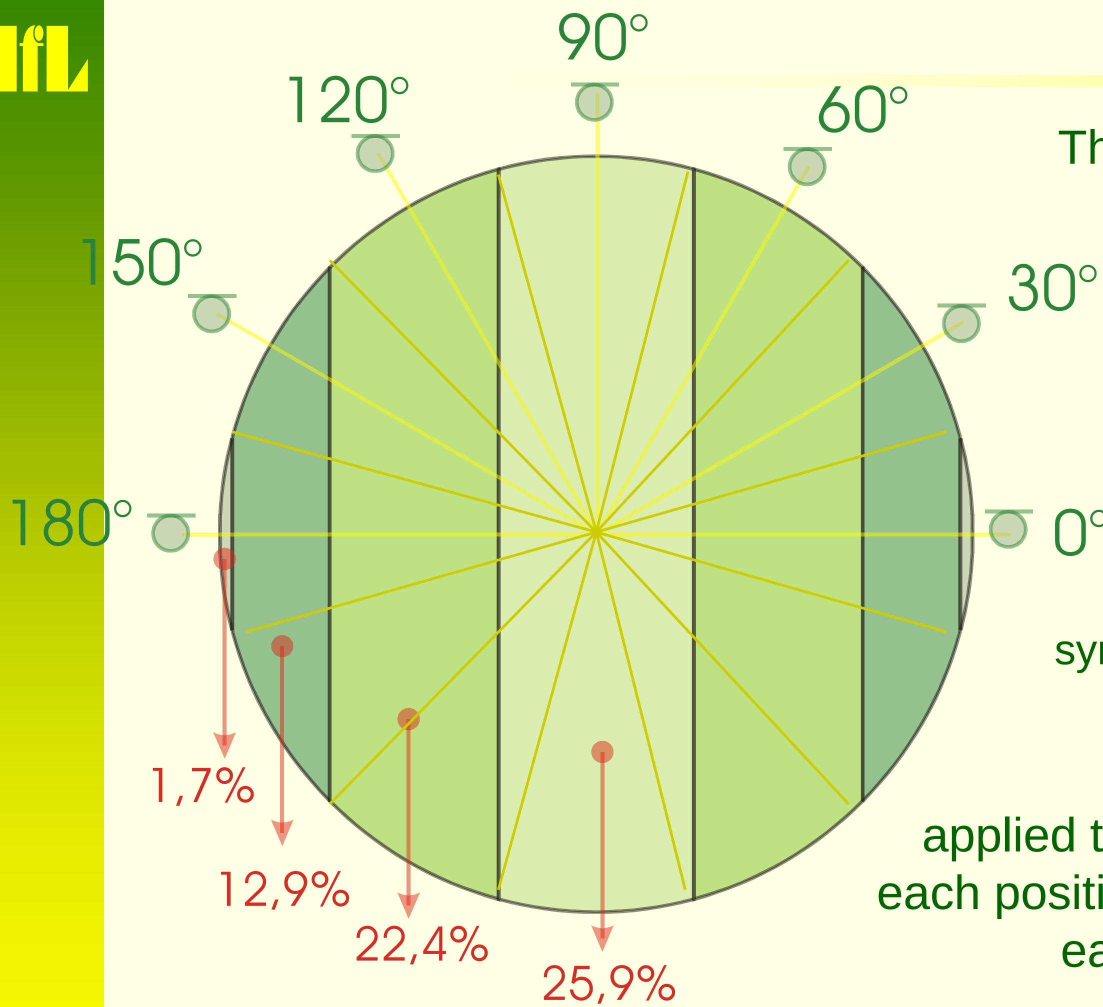


Spectra Winchester .300, distance 7.8 m, source- and microphone height 1.5 m

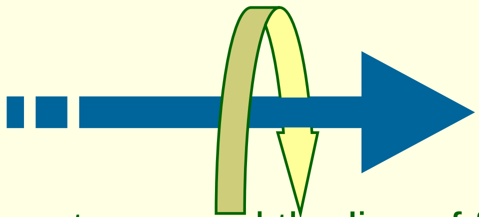
„An Overview on Military Weapon Noise: Its Physics and Annoyance“, Seoul National University, Korea, 2003

Total source energy

weighted contributions



The measurement at each angle represents the energy-flow density for different slices of the sphere.



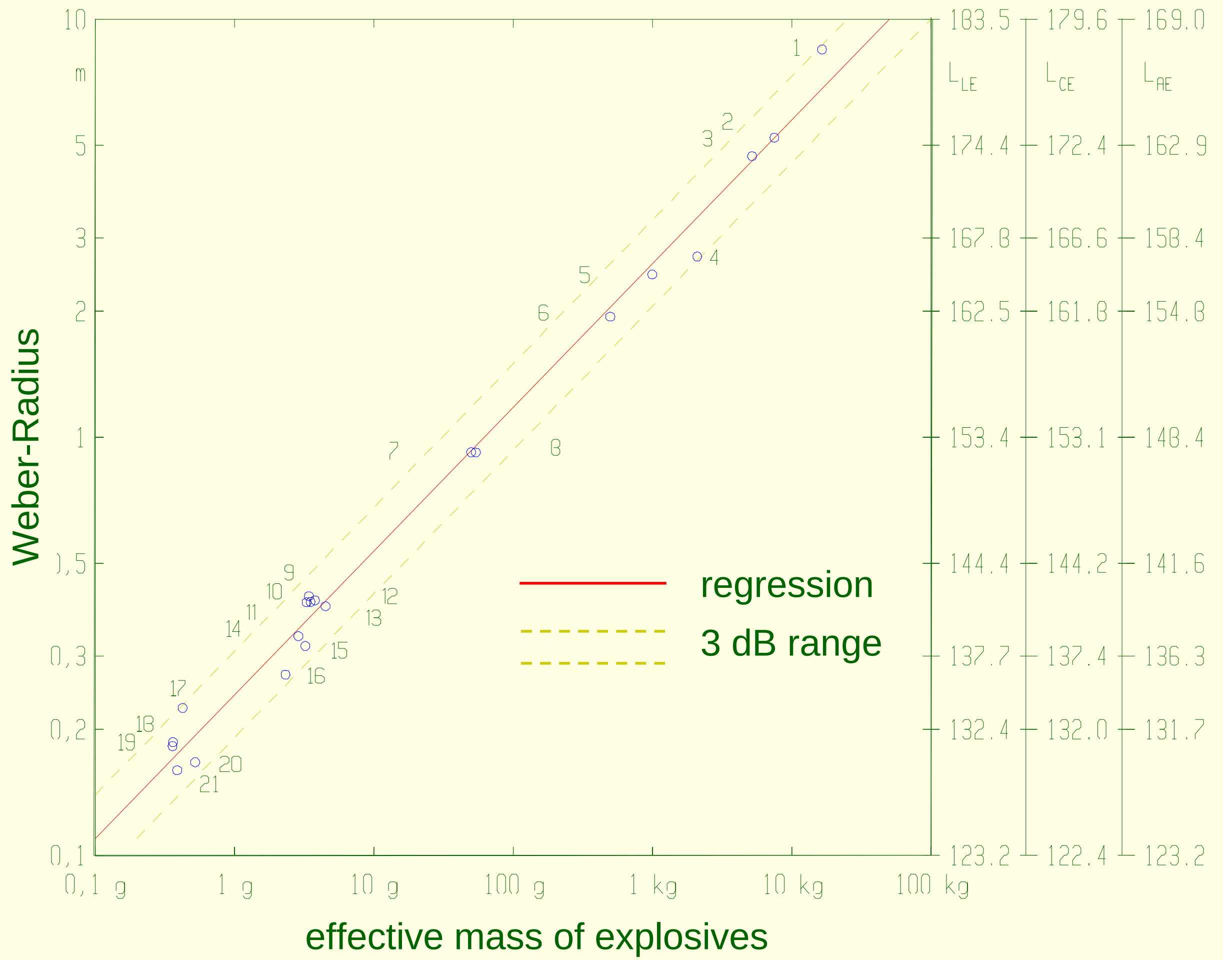
symmetry around the line of fire

Weighting factors must be applied to correct the contributions from each position with respect to the area that each angle is really representing.

For correlation purposes of sound energy with e.g. charge weight, this weighting was often neglected and was the reason for wrong conclusions.

Weber-Radius versus mass of explosives

effective mass for howitzers, cannons and rifles



1 = 16,5 kg TNT Demolition
2 = 120 mm KPz Leopard 2
3 = 105 mm KPz Leopard 1
4 = 155 mm Howitzer (5GB)
5 = 1 kg TNT Demolition
6 = 500 g PETN Demolition
7 = DM54 Demolition
8 = 20 mm SPz Marder
9 =.300 Winch. Hohlspitz
10 =.300 Winch. Vollmantel
11 = Mauser SR93 Rifle
12 =.300 Mag. Rifle
13 = 6,5x68 Rifle
14 = PSG 1 Rifle
15 =.243 Winch. Rifle
16 = 5,6x50 Rifle
17 = Pistol SIG
18 = Pistol P1
19 = 9 mm Signal pistol
20 = M-Pistol MP5
21 =.22 Hornet Rifle

Weber model

the description for muzzle blast and explosions

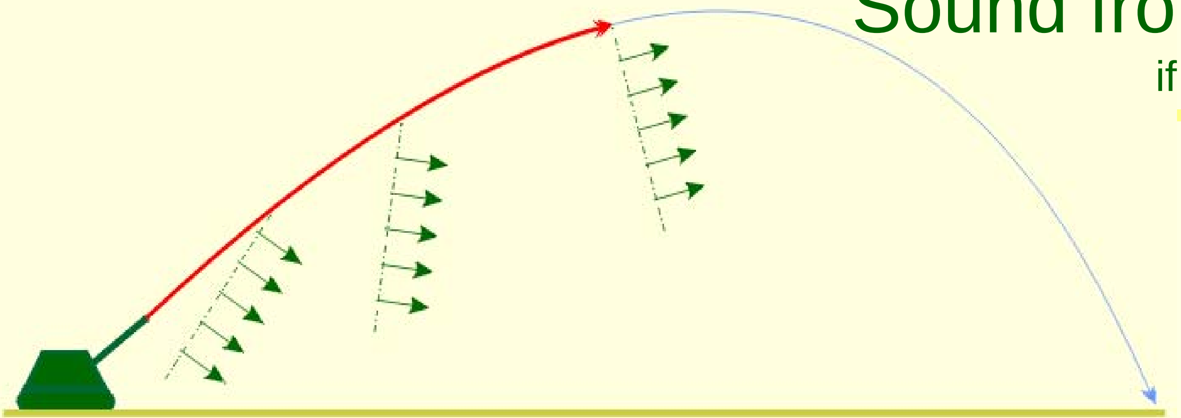
The Weber model

- is a simple model with only one free parameter, the Weber-Radius.
- predicts signals for muzzle blast and reports from explosion sufficiently reliable.
- provides Fourier-spectra and therefore all acoustical measures including frequency and time weightings are applicable.
- For noise prediction purposes it is good enough (Ups, we look at noise from the physical side, but at this stage it may be allowed.).

Status

Sound from the trajectory

if the projectile is supersonic

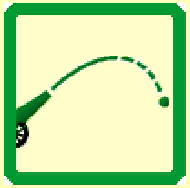


Projectile sound from ballistic trajectories looks complex and indeed, it is a rather challenge.

The WinLarm suite provides a little add-on called ‚Shooter' to depict the first problem: **the trajectory**.

Shooter evaluates all necessary parameter along the trajectory including local speed, flight angle and energy loss. It solves online the trajectory on the basis of the given initial conditions. Currently the most frequently used howitzers, cannons, rockets and small arms are in the program.

WinLarm's little helper to calculate the projectile sound from ballistic trajectories.



Shooter

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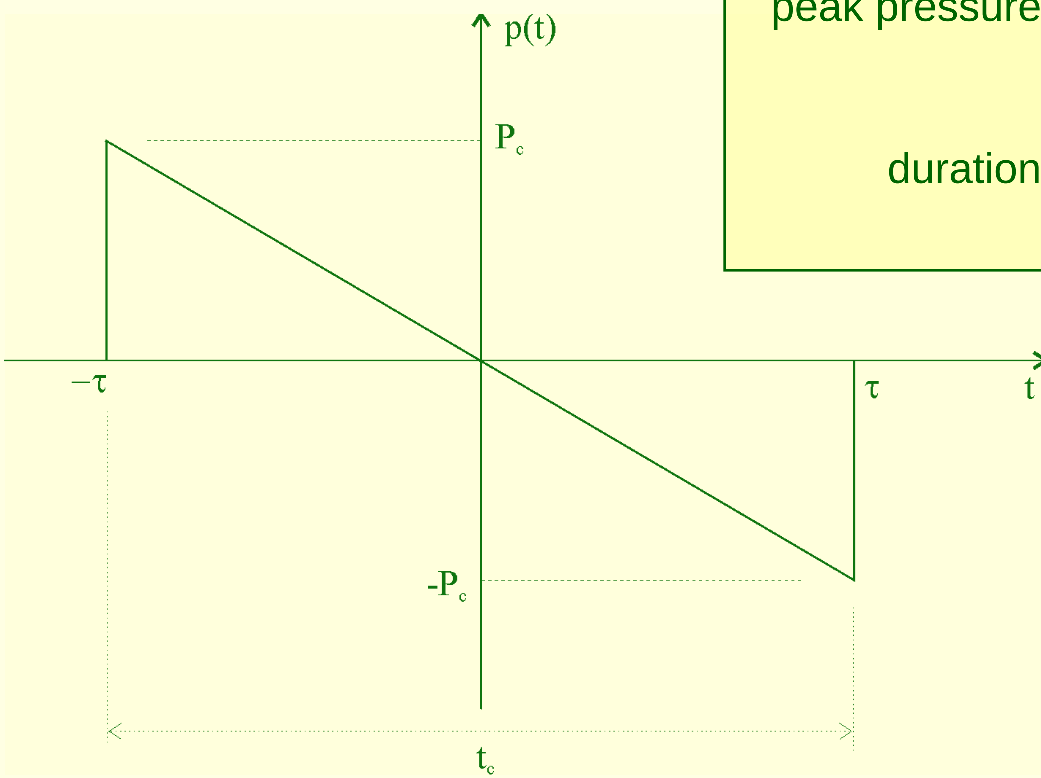
Non-Acoustical model

(Witham, 1952 - 1953)

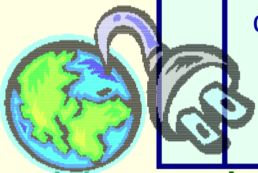
The shape of the projectile sound is a so-called N-wave



peak pressure $$P_c(O) = 0{,}53 P_{atm} \frac{\left(M^2-1\right)^{1/8}}{O^{3/4}} \left[\frac{d}{l^{1/4}}\right]$$

duration $$t_c(O) = \frac{1.82}{c_0} \frac{M}{\left(M^2-1\right)^{3/8}} O^{1/4} \left[\frac{d}{l^{1/4}}\right]$$

P_c	peak pressure
P_{atm}	ambient pressure
O	perpendicular distance to the trajectory
M	Mach number
d	diameter of projectile
l	length of projectile
c_0	speed of sound



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Pressure model TNO

basic formulas, deduced from the Witham theory

This model is defined in ISO 17201, part 4 (draft)

source level

$$L_E^D(r) = L_0 + 10\lg\left(\frac{d_b^3}{l_b^{3/4} r_0^{9/4}}\right) + 10\lg\left(\frac{M^{9/4}}{\left(M^2-1\right)^{3/4}}\right) - A_{nlin} - A_{geo}$$

non-linearity

$$A_{nlin} = 5\lg\left(1 + \frac{1}{2}\sqrt{1 + \frac{\left(M^2-1\right)}{r_0 k}}\,\ln\left(\frac{r + \frac{M^2-1}{2k} + \sqrt{r^2 + r\cdot\left(\frac{M^2-1}{k}\right)}}{r_0 + \frac{M^2-1}{2k} + \sqrt{r_0^2 + r_0\cdot\left(\frac{M^2-1}{k}\right)}}\right)\right)$$

geometric spreading

$$A_{geo} = 10\lg\frac{r^2 k + r\left(M^2-1\right)}{r_0^2 k + r_0\left(M^2-1\right)}$$

Must we really handle that...

or is there an easier way, may be as simple as Weber‘s energy model for explosions?

Restrictions of the pressure model

- ⇨The model is designed for straight trajectories.
- ⇨The model cannot describe the transmission to subsonic.

Keeping in mind that we must handle ballistic trajectories, where the projectile will slow down from supersonic to subsonic speed.

Can we use a simpler model?

Can we deduce a model from an energy concept instead of a pressure concept without violating acoustical correctness?

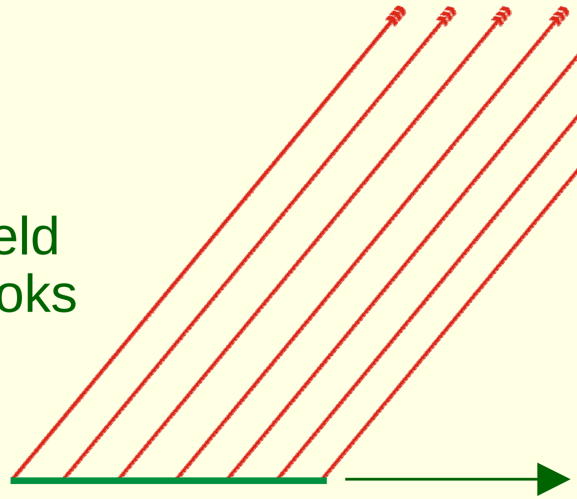
Yes, we can!

Cut and dried opinions

wrong views produce wrong models

It is not true

⇨ that the projectile sound field of a rifle or cannon shot looks like that:



⇨ that the geometrical spreading is 1/r or 10 lg (r/r_0).
However this holds for rockets approximately.

⇨ that deviations from 1/r or 10 lg (r/r_0) are primarily generated by non-linear effects.

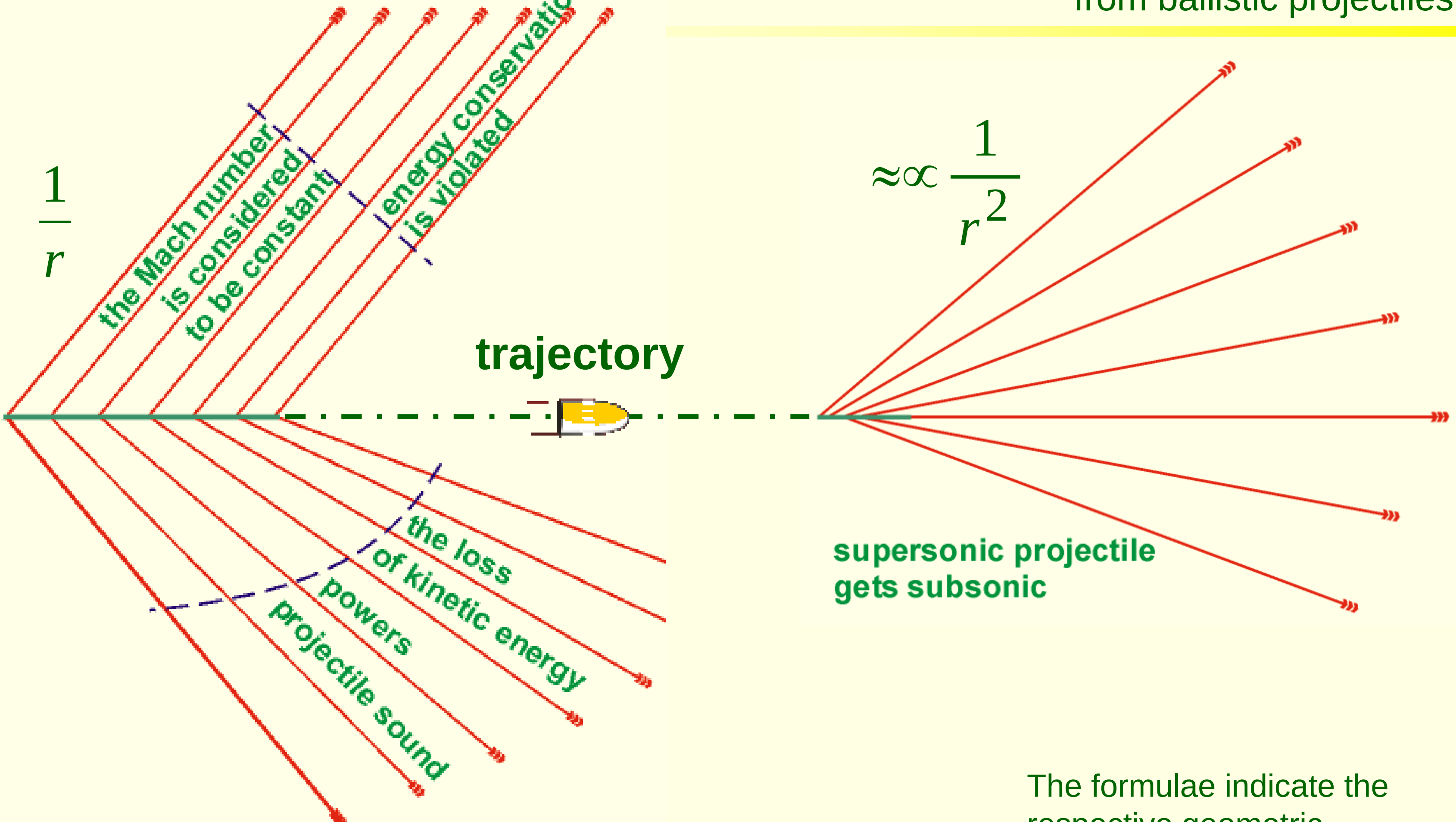
⇨ that pistols und shot guns do not produce projectile sound.

⇨ that levels from fast projectiles are higher than levels from slow projectiles.

⇨ that projectile noise does not occur in the direction of fire.

Energy of projectile sound

from ballistic projectiles



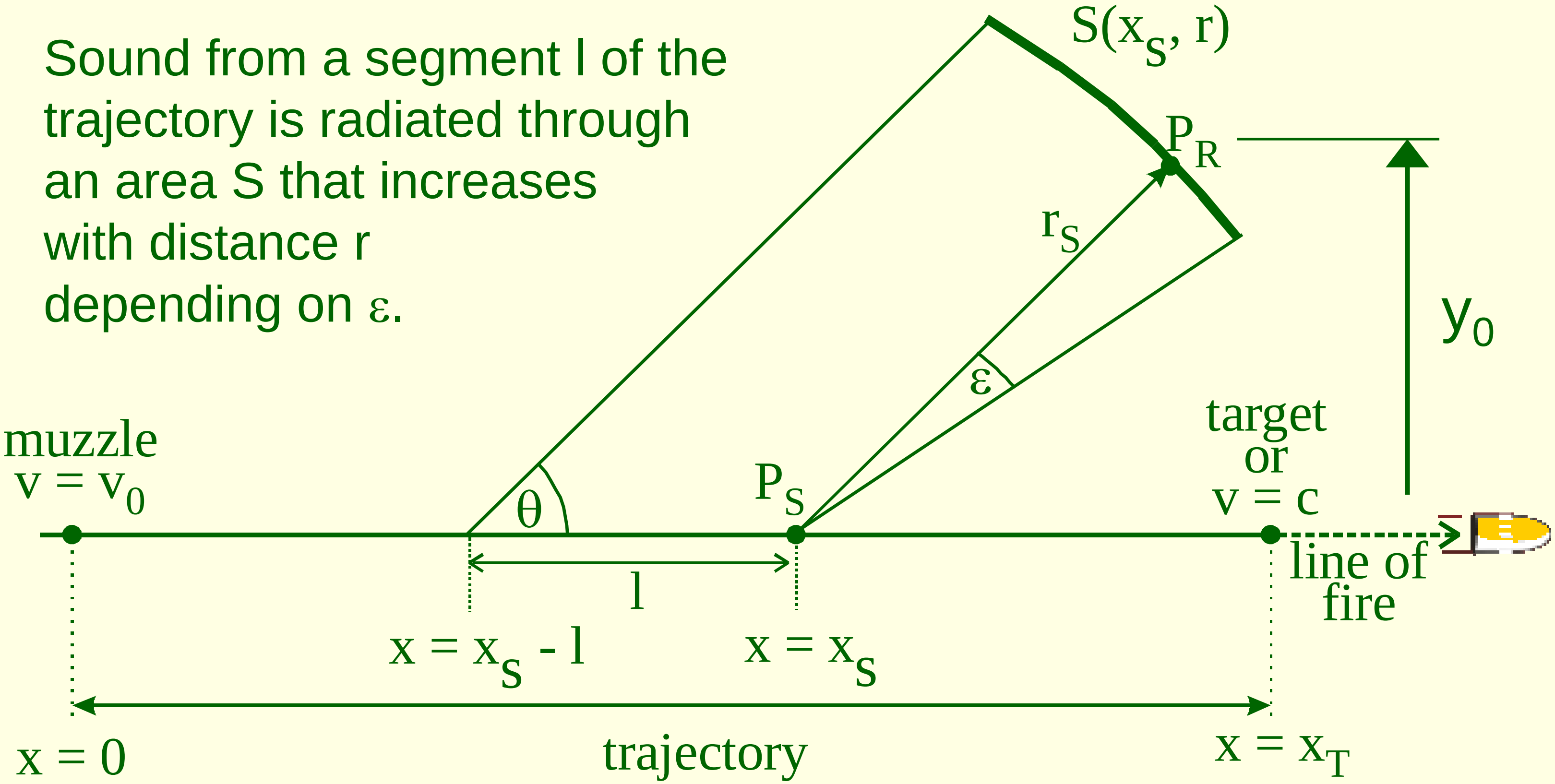
$$\frac{1}{2\pi l^2\left[\sin^2\theta_S\left(\frac{\cos\theta_S}{2}+\frac{r_S}{l}\right)+\frac{r_S^2}{l^2}\sin\left(\theta_S-\frac{\varepsilon_S}{2}\right)\sin\varepsilon_S\right]}$$

The formulae indicate the respective geometric spreading of energy.

Geometry

you can't get away without it …

Sound from a segment l of the trajectory is radiated through an area S that increases with distance r depending on ε.



$$(x_0 - x_S)^2 (v_0 + \kappa x_S + c)(v_0 + \kappa x_S - c) = c^2 y_0^2$$

$$x < x_S < x_0 \quad and \quad x_S < \left| \frac{c - v_0}{\kappa} \right|$$

connect to the archive on
www.ifl-acoustics.de
and download
‚seoul2003.pdf‘

Energy model [IfL]

basic formulas

This model is defined in ISO 17201, part 2 (draft)

kinetic energy loss along the segment l of the trajectory

acoustical efficiency ≈ 0,25

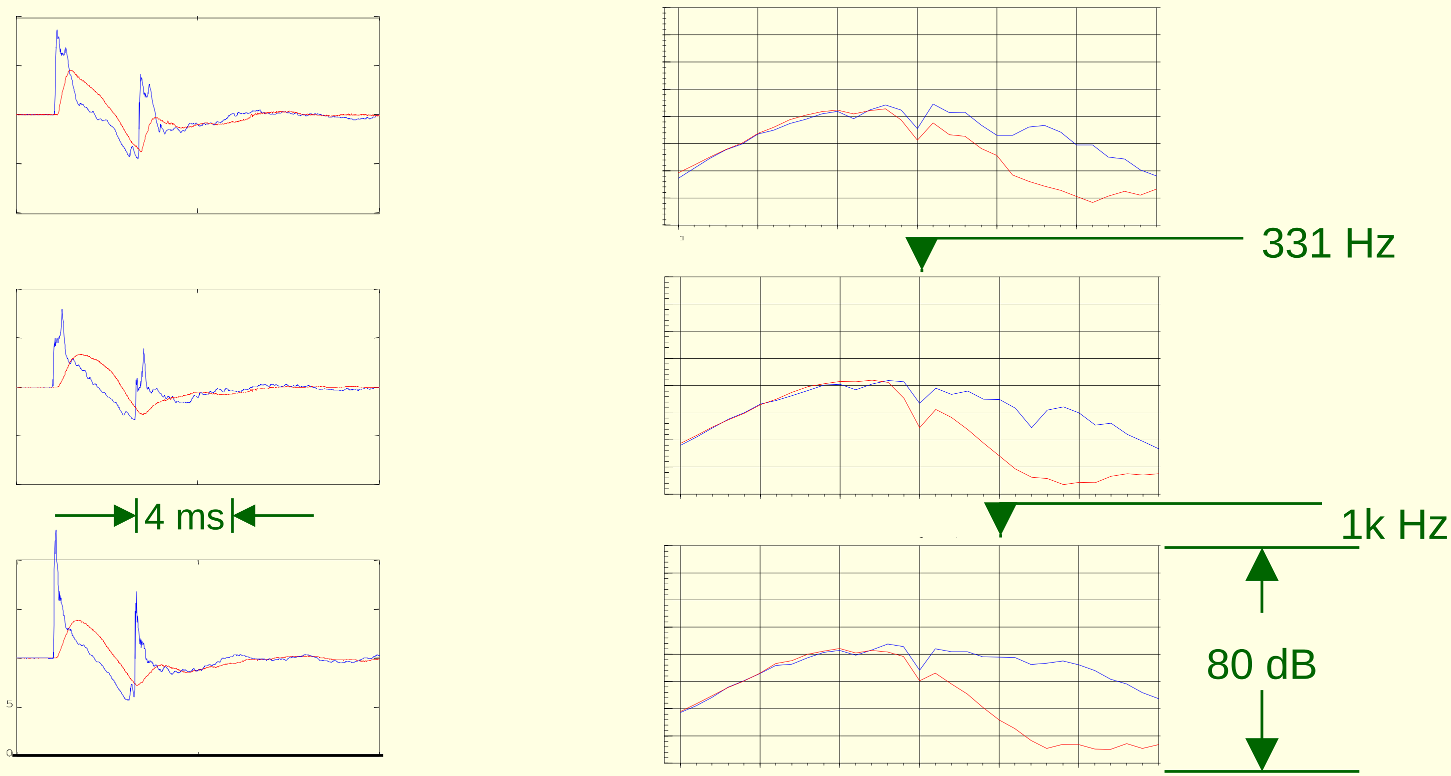
$$L_E^E(r_S) = 10\lg\left[\frac{\rho c}{p_0^2}\,\frac{f_{ac}\,e\,l}{2\pi l^2\left[\sin^2\theta_S\left(\frac{\cos\theta_S}{2}+\frac{r_S}{l}\right)+\frac{r_S^2}{l^2}\sin\left(\theta_S-\frac{\varepsilon_S}{2}\right)\sin\varepsilon_S\right]}\right]$$

geometric spreading

θ_s is 90° minus Mach-angle at the beginning of the segment l
ε_s is the difference between the Mach-angle at the beginning and end of the segment

Sonic boom of a howitzer shot

at 5 m height and at the ground



time histories

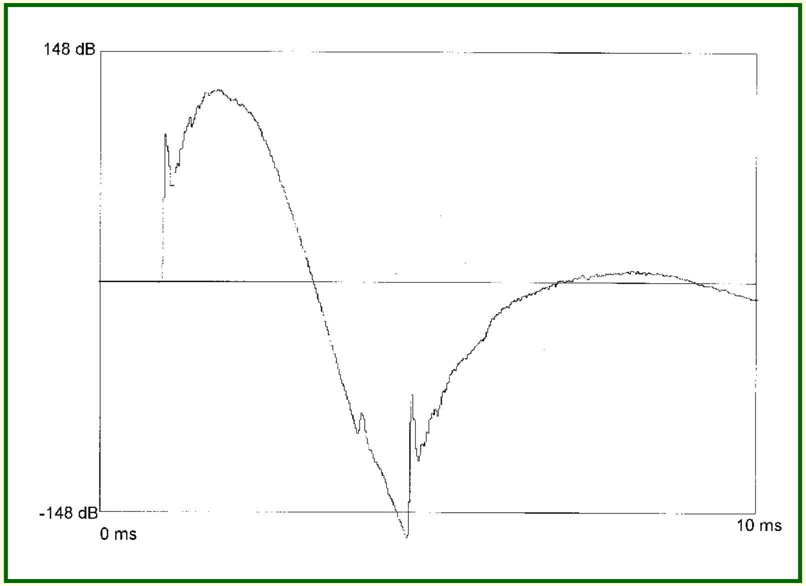
spectra

trajectory height 8 m at source point, measuring height 5 m (blue), at the ground (red), Mach number = 1.51, propagation path 100 m, up wind conditions

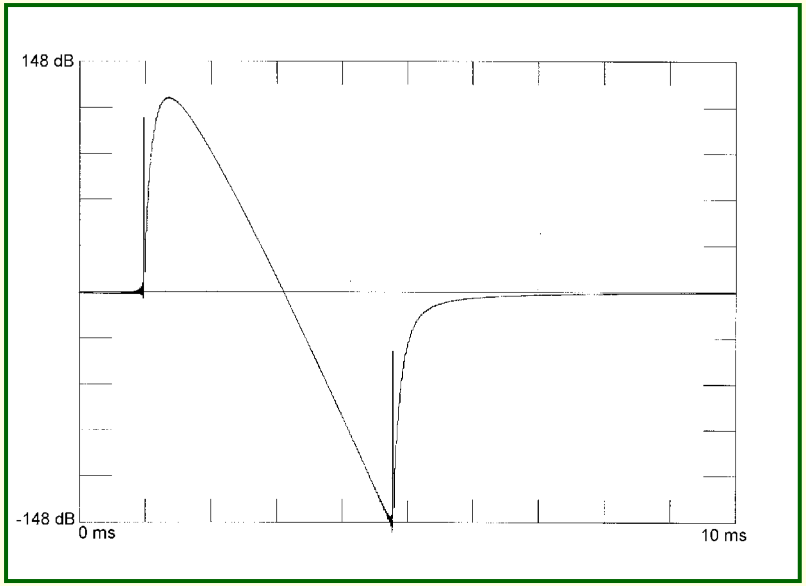
Measured signals at the ground

acoustical correctness helps to understand the result

measured pressure signal



calculated signal



The calculation superimposes two ideal N-waves, the direct wave and the reflected wave.

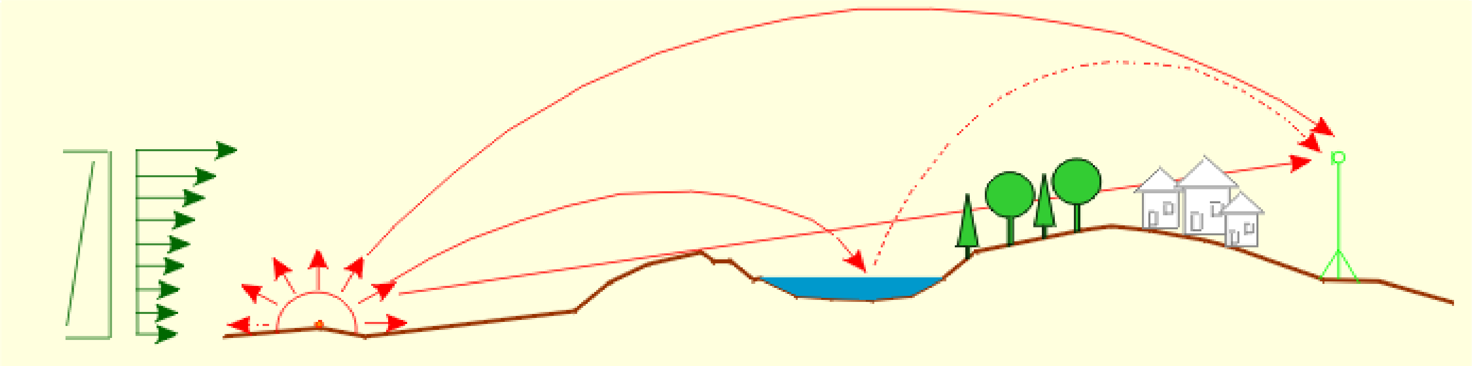
Because it is a cylindrical wave front, the reflection is considered for a spherical wave at complex impedance ground (grassy ground impedance).

Measurement and prediction agrees, if the source signal shape is assumed to be an ideal N-wave.

Status

Influences along the propagation path

most features are only well-known on an average scale



typical distance between source and affected residential areas 1 km to 20 km

Phenomena

- geometric spreading
- air absorption
- ground reflection
- curved rays due to wind and/or temperature gradients
- attenuation by residential areas
- attenuation by vegetation
- shielding by terrain

Weather

a never ending story in outdoor acoustics

Observations

- ⇨ The current weather has a tremendous influence on sound propagation.
- ⇨ ‚Current' here means weather on the basis of minutes.
- ⇨ Receiver levels may normally vary within a range of 10 dB from shot to shot fired minute by minute in downwind condition.
- ⇨ In up wind situations the range can be much wider.

Averaging

The way out is to average a series of shots and include so many shots that the desired ‚confidence' of the mean value is achieved.

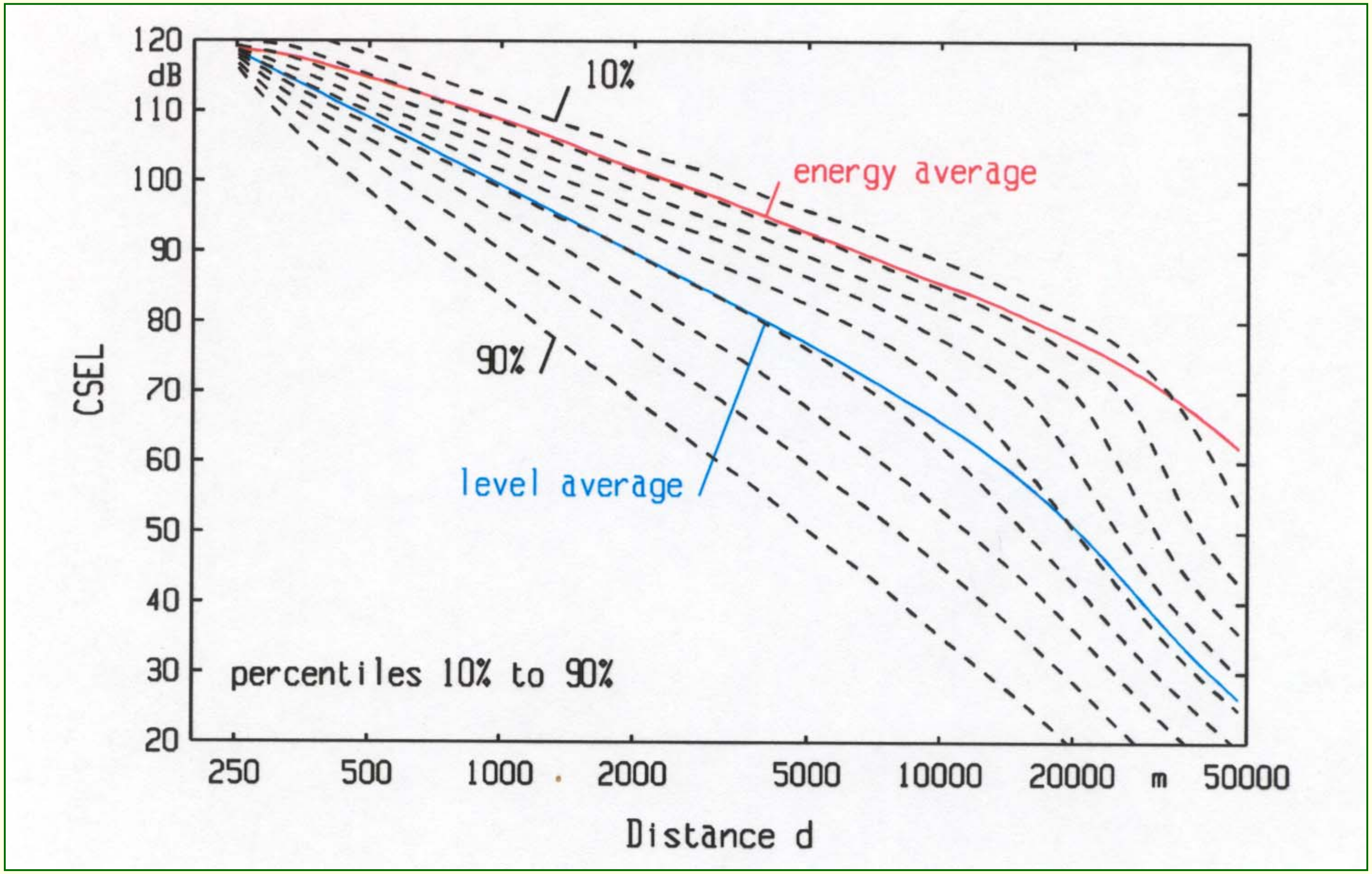
This really means averaging over weather situations that we cannot distinguish in terms of our weather measurements.

This average level must be well understood.

Expectation values

don‘t by surprised

In 90% of all cases the levels are measured significantly lower than the energy average.



Analysis based on more then 3000 shots measured by Schomer, CERL, USA, in the 80‘s

Status

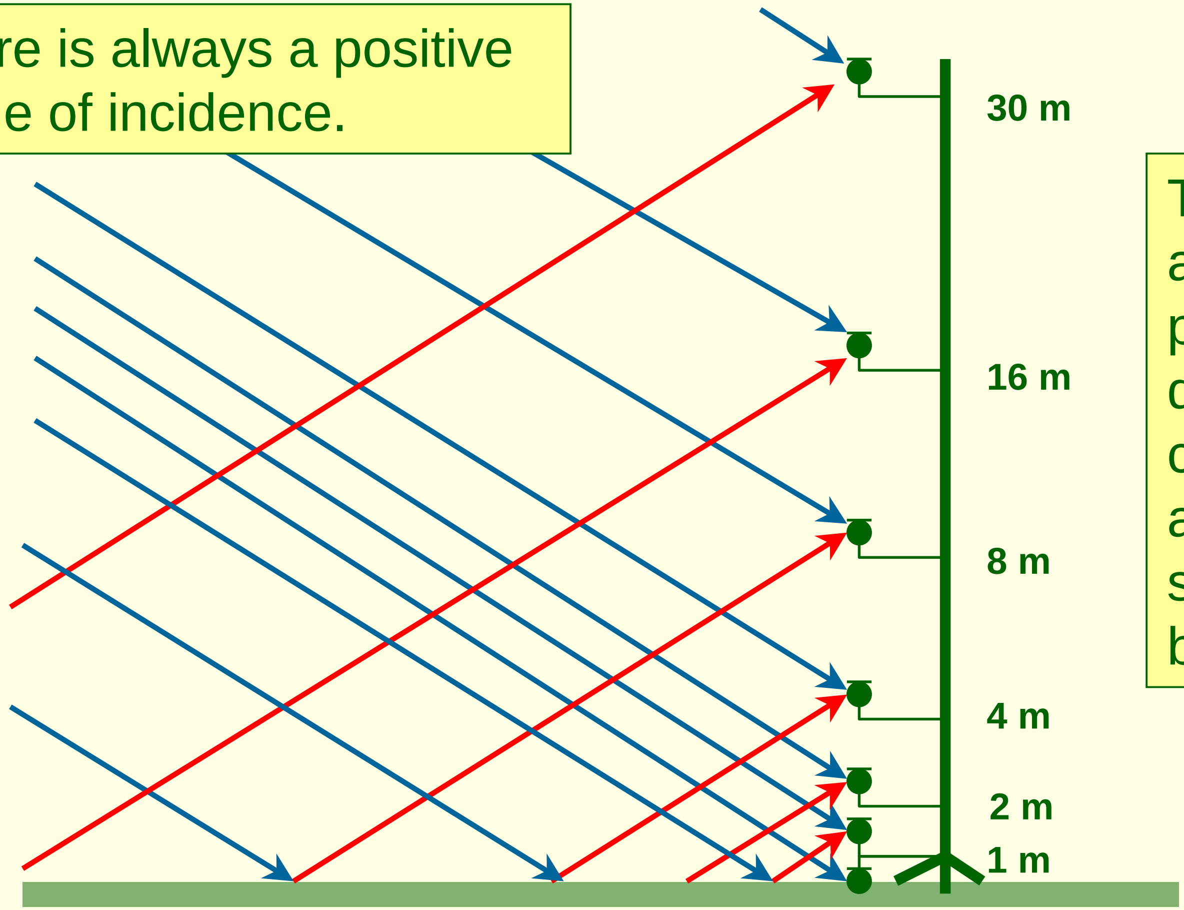
Coherence at the receiver

again acoustical correctness

There are always coherent direct and reflected waves.

There is always a positive angle of incidence.

There is always pressure doubling, cancellation and something in between.

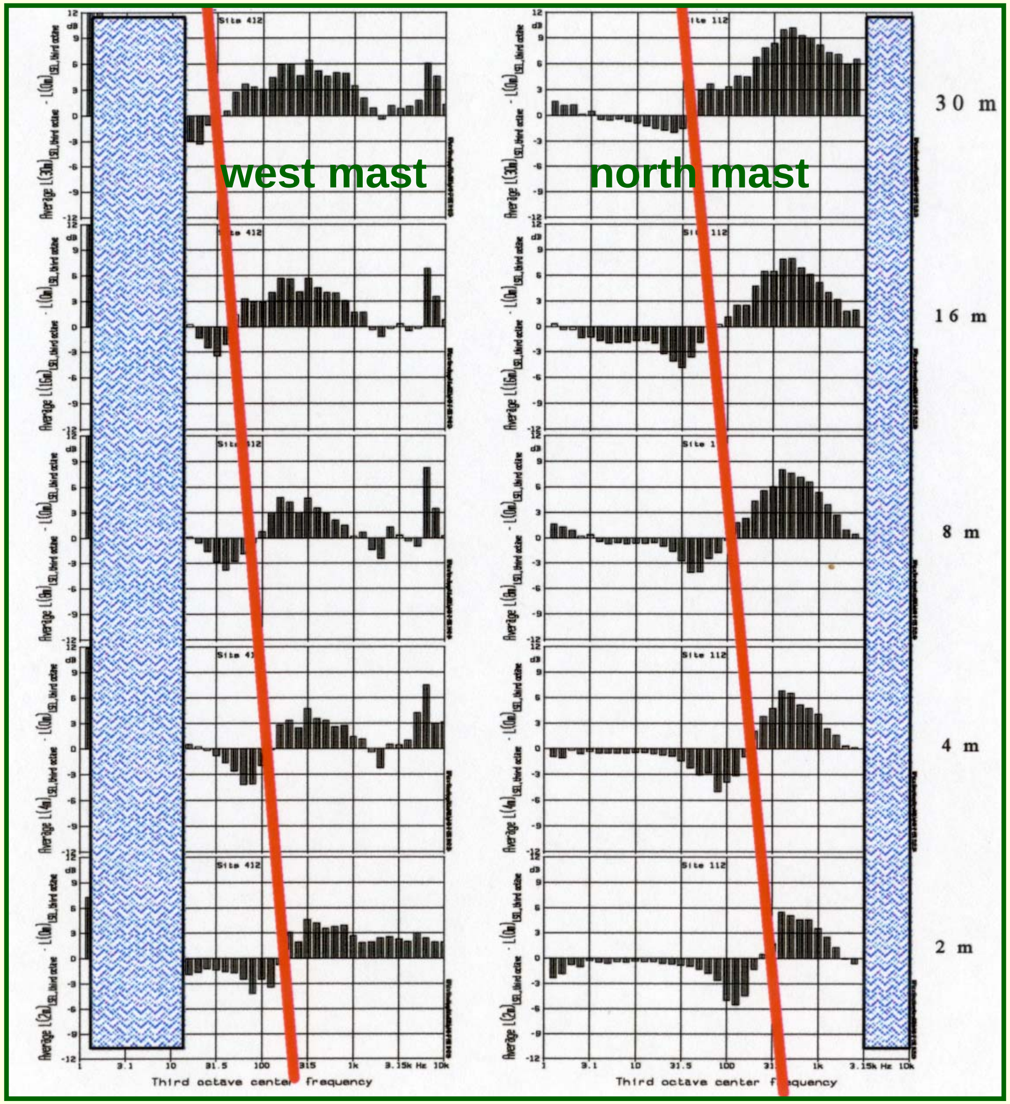


„An Overview on Military Weapon Noise: Its Physics and Annoyance“, Seoul National University, Korea, 2003

Receiver signals at different heights

difference to ground measurement

Results from „Norwegian Trials“



Observations

The ‚ground dip‘ shifts through the spectra.

The medium frequencies have higher levels in greater heights.

The low frequencies have higher levels closer to the ground.

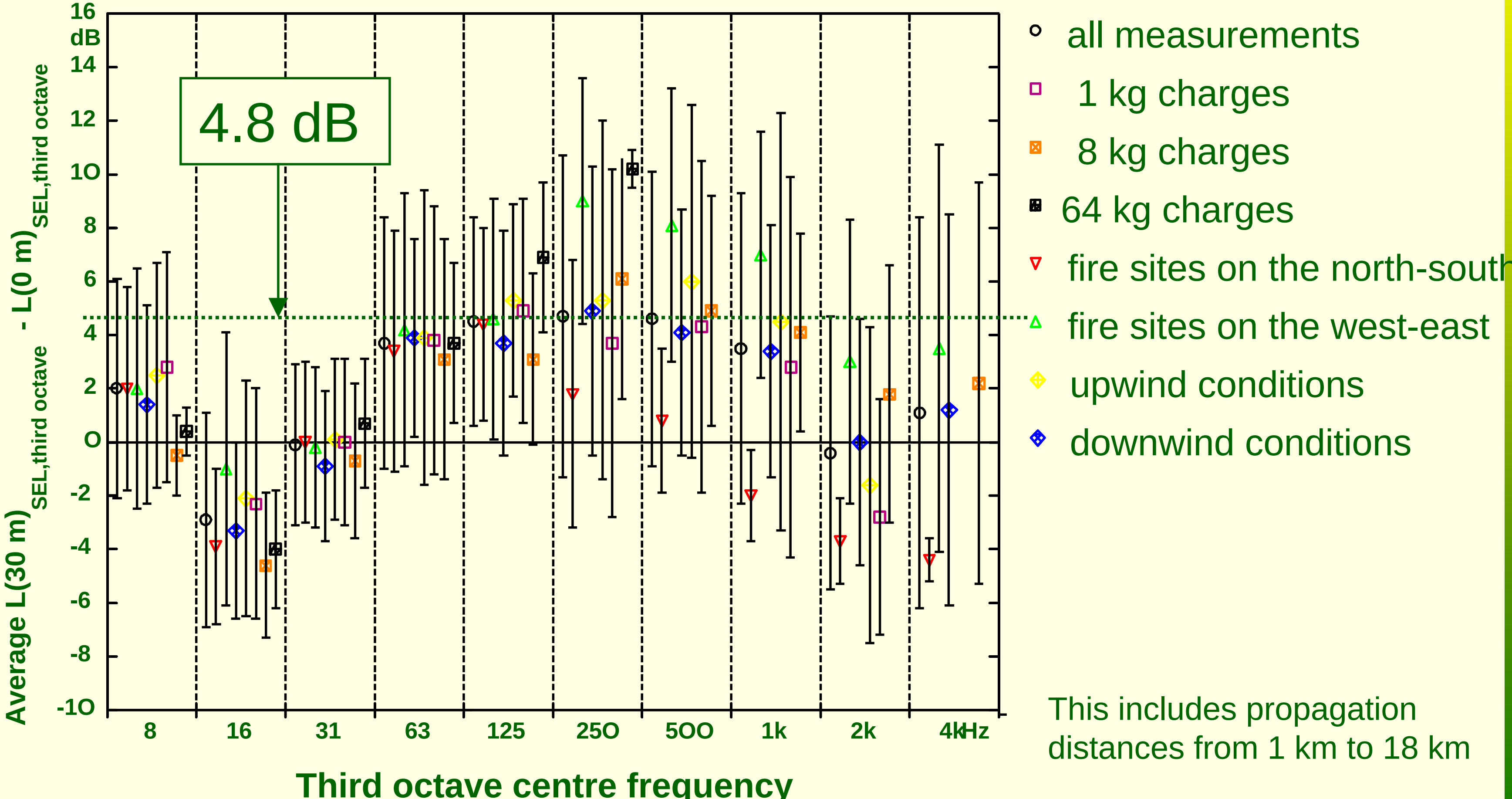
The cross-over frequency between these regions decreases with receiver height.

unreliable results

Receiver signals at different heights

difference between 30 m and 0 m measuring height

Results from „Norwegian Trials“



This includes propagation distances from 1 km to 18 km

The receiver site may determine the level

Things to keep in mind

- There is a significant influence of receiver height on the spectrum.
- There is a significant influence of the ground impedance of the receiver site.
- The average of third octave levels can differ by more the 10 dB.
- This influence is independent of propagation distance, source strength and weather.
- The receiver site determines this effect.

Status

Weightings

connecting sound to noise

Weightings connect the physical side to the human response side.
Do they really?

Once upon a time, we had weightings made for distinct purposes. The mothers and farthers of weightings needed simple filters in their meters to roughly take into account the features of human hearing. Then, they knew what they were doing: The best they could.

There were a lot of such weightings: A, B, C, D in combination with ‚Fast' and ‚Slow' or LEQ or SEL.

Today, it looks like A-weigthing won the competion: At least Europe unifies on $L_{A,DEN}$.
That is reducing the world of noise to 1000 Hz. Neither nature nor our ears will obey.

Weightings

we are making „regress“ not progress

A-weighting is wrong for low frequencies.

A-weighting is wrong for high frequencies.

Modern technique could solve the problems of the mothers and farthers of weightings but we are going to even simplify more, having forgotten what weightings are for.

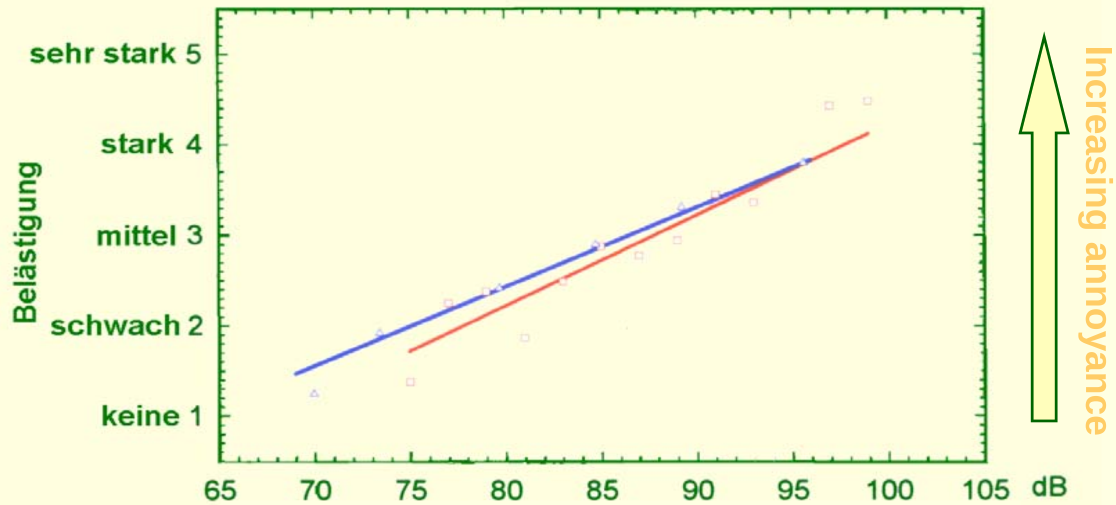
However, I will continue and report what is done to weight the sound in order to assess the noise for correlation purposes with annoyance.

Annoyance

I‘m skating on thin ice ...

Asking people is not a physical method. So, there is no clear opinion that all scientists share on how to rate the shooting noise from large weapons.

I don‘t dare to translate the German words because the human response side depends on the precise wording, they say.



ASEL of vehicle pass-by

CSEL of shooting sound

One result of a rather simple method called ‚paired-comparison-test‘ should point out what one can conclude in general.

> The annoyance is the same,
> if the CSEL of a single shot
> compares to the ASEL of a vehicle pass-by.

How to define a rating level ...

small arms

The paired comparison test result shows the general procedure used to achieve an objective rule to assess different kinds of noise.

Thinking of traffic noise as a standard noise,
the human response to all other kinds of noise is compared to the annoyance of this standard noise.

Either a constant or a level dependent adjustment is defined that has to be added to the physical measure for that noise,
or a weighted sound measure is defined that correlates best to annoyance.

It is generally accepted that the ASEL of shooting noise from small arms (calibre < 20 mm) needs an adjustment of +12 dB to rate the annoyance with respect to traffic noise.

How to define a rating level ...

large weapons

Social surveys in Germany yield that long term average CSEL of shooting noise from large weapons predicts the same annoyance as long term average ASEL of traffic noise.

Therefore,
no adjustment is needed for this kind of shooting noise if measured and predicted as long term average CSEL.

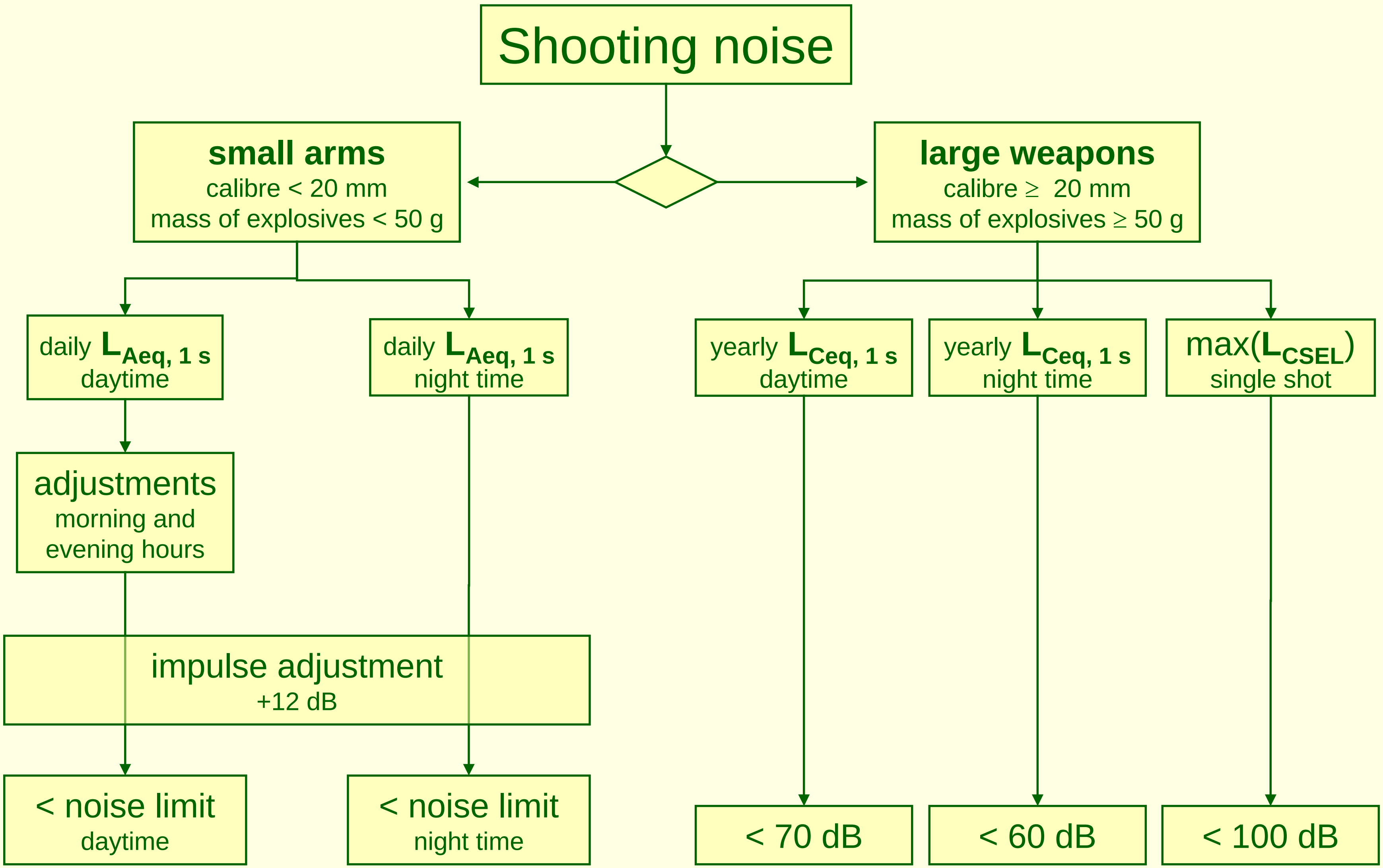
In Germany this is the key statement for the assessment of shooting noise for large weapons.

Status

- Introduction
- Military weapons
- Blast sources
  - Explosions in air
  - Muzzle blast
  - Projectile sound
- Long range propagation
- Reception of blast sounds
- Human response to blasts
- **Assessment of shooting noise in Germany**
- Summary

Assessment of shooting noise in Germany

concept and rules in general ...

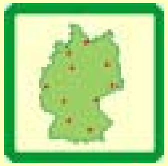


WinLarm‘s noise contour map

a dedicated tool for noise management

The software suite WinLarm provides a tool to analyse the noise situation and to look whether or not the noise load comply with the noise limits.

WinLarm‘s module „Mapper“ helps to analyse the noise load in the vicinity of a military facility.



Mapper

Status

Summary

- Blasts from weapons are somehow special. Their special features are high energy, impulsiveness, low frequencies, strong directionality and long range propagation.
- It pays off to stay on the physical side of the challenge as long as possible.
- The key to understand the receiver signals is to include the ground reflection and obey the rules of acoustical correctness.
- The Weber-Model for muzzle blast and the energy model for projectile sound are the starting points to compile a reliable prediction model for sound levels to correlate to annoyance.
- The prediction of sound propagation over long distances adds a lot of uncertainties to the result.
- However, long term average C-weighted sound exposure levels seem to be sufficiently reliable for correlation purposes to annoyance.

Acknowledgement

Most of the results presented here were achieved due to the strong and sustained promotional support of the German Ministry of Defense.