

Bathymetric and Seasonal Effects on the Propagation of Airgun Signals to Long Distances in the Ocean

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Abstract— Marine seismic exploration uses air guns or air gun arrays to generate high energy, short duration acoustic pulses deep into the ocean floor but some of the seismic/acoustic energy remains in the water column and can propagate to considerably distances. This may cause disturbance to marine life and there is evidence that this noise can cause reactions on the behavior of fish resulting in reduced catches. This has resulted in severe conflict of interest between the petroleum and the fishing industry. The ultimate goal of the work that is presented here is to be able to estimate the minimum distance from a seismic survey to avoid significant negative effects on fish behavior and fish catch. We have developed a propagation model, based on ray theory that can deal with range dependent bathymetry and depth dependent sound speed profiles. This paper describes briefly the model and its capabilities, followed by the presentation of several relevant examples of propagation over range dependent bathymetry with typical sound speed profiles from different geographical locations and seasons. The main conclusion is that both the bathymetry, the geo-acoustic properties of the bottom and the oceanographic conditions have significant impact on the propagation of seismic noise. The focusing of sound, caused by the bathymetry and/or sound speed profile, may create regions with hot spots where the sound level is significantly higher than normally expected. Common range dependent sound propagation methods for cylindrical and spherical spreading, e.g. $-10\log(r)$ and $-20\log(r)$, are also compared to the modeled results.

I. INTRODUCTION

There are two issues involved with the impact of seismic noise on marine life. The first is acoustical and concerns the propagation of transient sound pulses in an ocean. The other is mainly biological concerning the sensitivity and how the fish or sea mammals react to the sound. In Fig. 1 an illustration of how impulsive sounds may propagate over a layered sea bed can be seen. Sounds hitting the bottom with an angle less than the critical angle, θ_{crit} , will experience almost total reflection and can therefore propagate to very long distances. If sounds hit the bottom with an angle larger than θ_{crit} most of the energy will be transmitted into the bottom and consequently not propagate far.

This paper is mainly about the acoustical issue, but also shows examples on how startle thresholds in fish can be used in combination with the modeled results to create an acoustical-biological model.

The sound propagation model used in this study is based on ray tracing and can deal with range dependent bathymetry and

depth dependent sound speed profiles ([1], [2]). The bottom is modeled as a sedimentary fluid layer over a solid elastic rock with the parameters being the seismo-acoustic properties of the sediments layer and the rock with compressional speed, shear speed and absorption. The model simulates the total sound field, both in the time and in the frequency domain. It also generates the full-waveform of the transient signal, which is essential since this allows for the extraction of a number of different characteristics of the sound field. In the current version the model derives two measures; the sound exposure level (SEL) which is an energy measure, and the peak pressure level (PPL) [3].

In this report, except for the modeling of the real situation, the seismo-acoustic model is simple, assuming the bottom to be a homogenous fluid with sound speed 1700 m/s, density of 1500 m/s and bottom absorption of 0.5 dB per wavelength. These parameters results in a frequency independent bottom reflection loss shown in Fig. 2. The critical angle is 28° and at lower angles the absorption gives a reflection loss that varies with angle, but is less than about 1 dB.

The sound propagation model uses a Ricker pulse as the source signal. This is a commonly used time signal when modeling seismic airgun sounds [4]. The Ricker pulse used has a center frequency of 50 Hz.

A sound propagation model like the one described in this paper could be used to plan noisy underwater activities, e.g. seismic surveys, such that the disturbance of sea mammals is minimized. This is, as mentioned, not treated specifically in this paper, but has recently been submitted as an independent

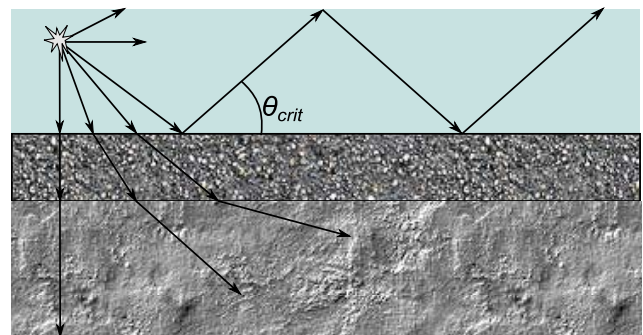


Figure 1. Illustration of sound propagation over a layered sea bed..

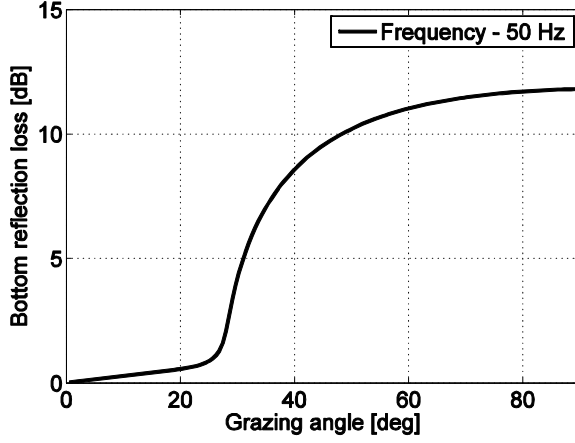


Figure 2. Bottom reflection loss as function of incident grazing angle. The loss is calculated for a bottom sound speed of 1700 m/s, density 1500 kg/m³ and bottom absorption of 0.5 dB per acoustic wavelength. The water sound speed is 1500 m/s and the density is 1000 kg/m³.

work [5].

Common sound propagation methods use the asymptotic behavior of spherical and cylindrical spreading, i.e. $-20\log(r)$ and $-10\log(r)$ respectively [6]. The TL for a sound in a waveguide, combining the two asymptotes, can be written

$$TL = 10 \cdot \log_{10} \left(r^2 \cdot \left(1 + \frac{r^2}{r_t^2} \right)^{-\frac{1}{2}} \right) \quad (1)$$

where r is the horizontal distance from the source to the receiver and r_t is the transition area where the TL goes from spherical to cylindrical. A reasonable value for r_t is a value close to the water depth.

In many real scenarios these methods are too simplistic, especially when the bathymetry and/or sound speed profiles varies. This will be demonstrated in the following sections. A real measurement of seismic shooting, ranging from approximately 30 km down to a few hundred meters, will also be shown to demonstrate the changes in sound propagation.

Sound absorption in the water is also a term in the TL function, but for the ranges and frequencies in this study this is not important and is left out of the expressions in this paper ([7], [8]). It is, however, included in the computer model.

II. BATHYMETRIC EFFECTS

A. Pekeris Waveguide

As a reference case we have used a Pekeris waveguide. This is a classical case in underwater acoustics and consists of a pressure release surface and a flat penetrable bottom [9]. Both the water and the seabed have constant sound speeds and densities. In Fig. 3 the time responses for different ranges can be seen. The dashed red line corresponds to rays striking the bottom with the critical angle. The expression for this line is

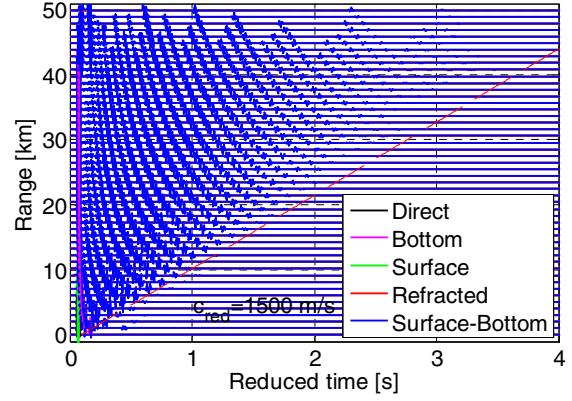


Figure 3. Time responses of a Pekeris waveguide with constant water depth 300m and constant sound speed 1500m/s. The sound speed of the bottom is 1700m/s, which gives a critical angle 28 deg. The dotted line shows the critical angle effect.

$$t_{red} = \frac{r}{c_0} \left(\frac{1}{\cos\theta_{crit}} - 1 \right) = r \left(\frac{c_b - c_0}{c_0^2} \right). \quad (2)$$

As mentioned before, rays that propagate at angles closer to the horizontal plane than the critical angle experience almost no bottom reflection loss and may therefore propagate to long distances. Rays with steeper angles will experience higher reflection losses and die out quite rapidly with range. Thus the time duration of the impulse is directly determined by the ratio of sound speeds in the water and the bottom. This estimate of the time duration of the channel impulse response assumes that the bottom is fluid homogenous and flat, but the estimate may also be useful in other cases with moderately range dependent depth and with solid or layered bottom.

The PPL and SEL as function of range can be seen in Fig. 4. The levels follow the asymptotic behavior mentioned earlier.

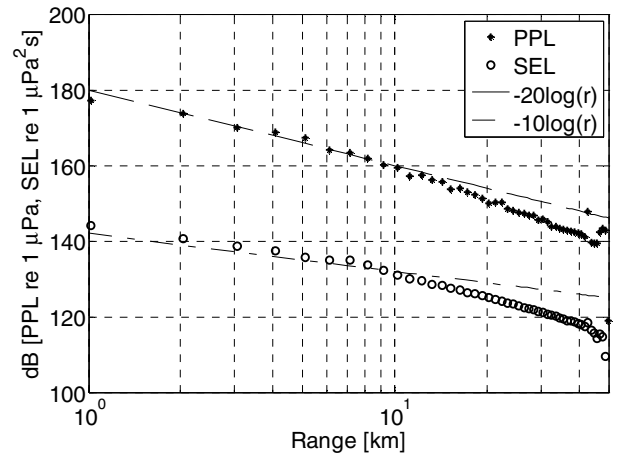


Figure 4. PPL and SEL as function of range for a Pekeris wave guide. The peak level tend to decay with distance at a rate close to $20 \log(r)$ whereas the SEL values decays with $10 \log(r)$. At longer ranges the two values decay at steeper rates due to reflection loss caused by bottom absorption.

B. Lloyd Mirror Effect

In open deep water the sound field is dominated by the direct signal and the surface reflected signal. In the case of a flat ocean surface the direct and surface reflected signals have the same amplitude but the surface reflected signal have opposite polarity (sign). At long ranges, especially at low frequencies and when the source is located close to the surface, there is therefore destructive interference resulting in a $40\log(r)$ transmission loss.

C. The Principle of Reciprocity

The principle of reciprocity is a useful tool in linear acoustics and system theory. It states that a pressure in position B due to a source in position A will be the same as the pressure in A due to a similar source in B [9]. This principle is even valid when the sound undergoes several reflections, such as from the bottom and surface in the ocean, on its way from the source to the receiver.

D. Downslope and Upslope

The next cases are two simple bathymetries; one with an upslope part and one with a downslope part. In Fig. 5 the two modeled cases with the ray traces can be seen. The decreased

water depth in the up sloping case clearly increases the density of rays in the water column at long distances. For the opposite case the density of rays clearly is decreased. This leads to an energy distribution that differs from the simpler Pekeris waveguide and which does not follow the asymptotic behavior described earlier (see Fig. 6).

III. SEASONAL EFFECTS

Near the surface there is a layer where the temperature will be subject to daily or seasonal changes in heating or cooling as well as from the mixing of water masses as a result of ocean wave action. Below this surface layer there may be a seasonally dependent thermocline, in which sound speed decreases with depth because the temperature decreases with depth. During summer the gradient is often steep as a result of warmer surface water, while in winter the effect is less pronounced. The gradient and the thickness of the layers mentioned above will vary according to geographical position, season, time of day, and meteorological conditions. Beneath this layer is the main thermocline, where temperature decreases with depth with a gradient less affected by surface conditions. At even great water depth, the temperature remains essentially constant, but the sound speed begins to increase with depth as a consequence of increasing pressure.

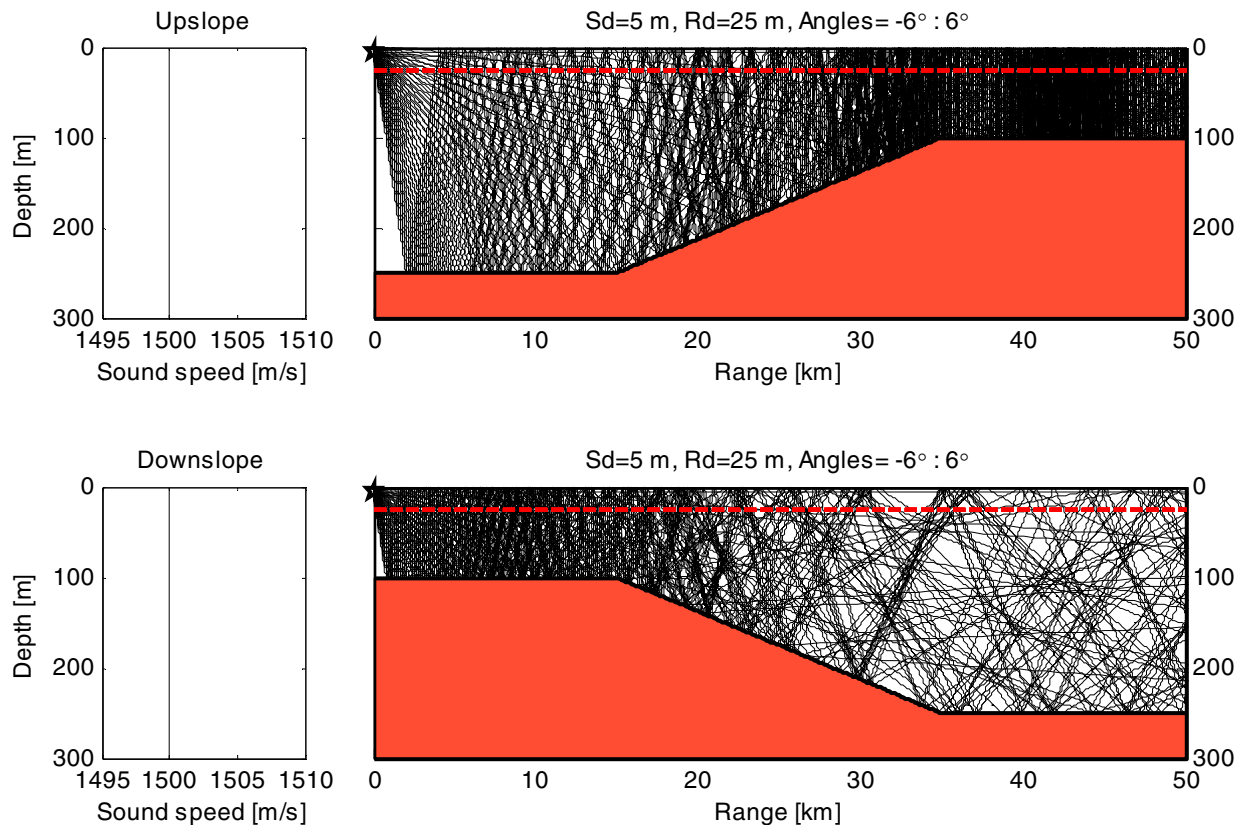


Figure 5. Ray traces in the case of up sloping and down sloping bottom. In both cases the depth changes with 150 m over a distance of 20 km, from 15 km to 35 km away from the source position. The sound speed in water is constant equal to 1500 m/s.

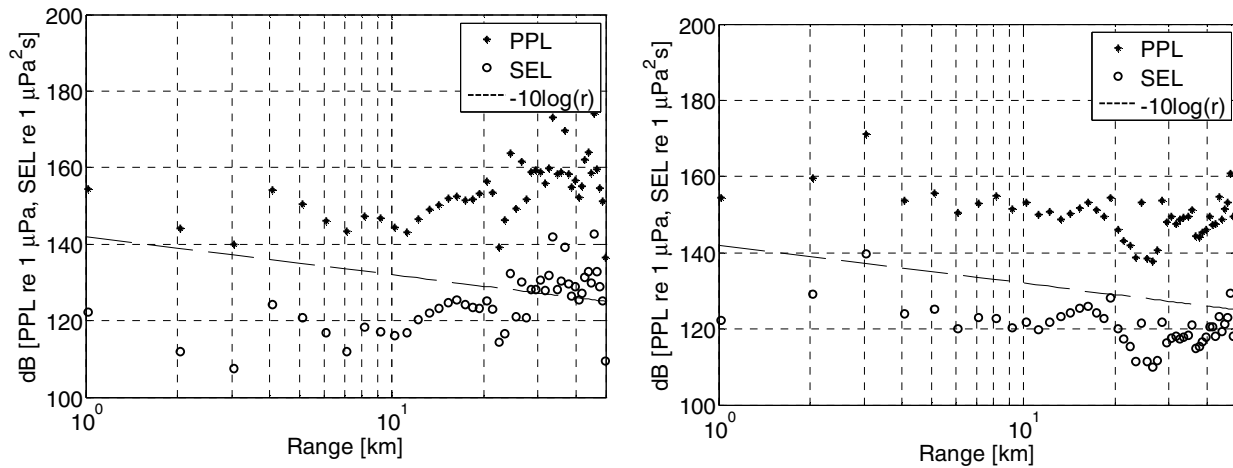


Figure 6. PPL and SEL as function of range for the two cases with sloping bathymetry. Upper: Upslope bathymetry. Lower: Downslope bathymetry.

In the next subsection two typical sound speed profiles, winter and summer, are modeled. The typical winter sound speed profile, represented with the March profile, has a sound channel near the surface generated by the relative cold water and low sound speed near the surface. In the summer, the temperature in the upper part of the ocean is higher, leading to a negative sound speed gradient down to about fifty meters depth as exemplified with the August profile. Below that depth

the water temperature is almost constant at all seasons and the sound speed increase slightly due to the pressure effect.

A. Winter and Summer Conditions in the Norwegian Sea

The illustration in Fig. 7 shows the ray traces from a source at 5 meter depth out to a distance of 10 km under winter (March) and summer (August) conditions. The bottom is

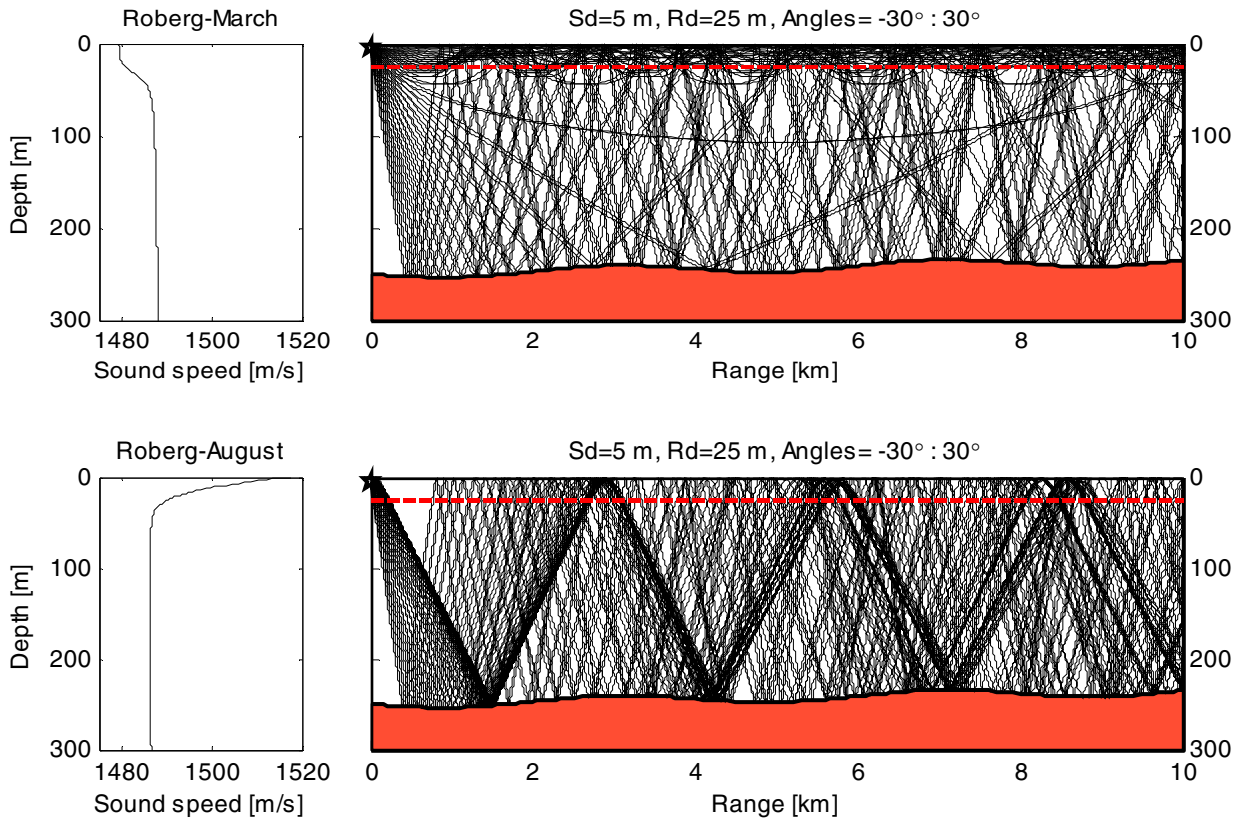


Figure 7. Sound speed profile and rays for winter (upper) and summer (lower) conditions in the Norwegian Sea. The source depth is 5 m the initial rays at the source span the angular interval of $\pm 30^\circ$.

slightly undulating at 230 to 250 m depth.

The sound level distributions, as function of range from the source and depth, are illustrated in Fig. 8. Under winter conditions there is a significant sound channeling effect near the surface (see Fig. 7). This means that signals from shallow sources, such as air guns, will propagate with approximately cylindrical spreading ($10\log(r)$) to large distances.

For summer conditions the negative sound speed gradient in the upper layers bend the rays down towards the bottom. Thus the bathymetry and the acoustic properties of the bottom (roughness, transmission, etc.) play an important role in the propagation of the airgun signals. The general trend is a decay rate of $20\log(r)$ with peaks at regular intervals, in this case at 3 km, 5.5 km and 8 km.

The sound channeling effect during winter condition gives significantly higher sound levels in the upper 50 meters than at deeper depths. As can be seen in Fig. 7 many of the rays does not reach the bottom, consequently any variations in the bathymetry does not affect the result as much. During summer conditions the opposite happens; the increased water temperature near the surface bends the rays downward to the

bottom, making bathymetric variations even more important.

IV. A REAL CASE

During the summer in 2009 the Norwegian Petroleum Directorate conducted a seismic survey in the field Nordland VII outside Vesterålen, Norway. During this survey the Institute of Marine Research (IMR) measured the airgun sounds both at the bottom and at the surface. Fig. 9 shows the real scenario that also was modeled. The bathymetric information is taken from the log file of the seismic survey vessel. The water depth increases approximately with 100 m in the range interval from 5 km to 20 km. The principle of reciprocity has been used in the modeling. More thorough descriptions of the modeling are found in [4] and [5].

The measurements taken during the survey, ranging from approx. 100 m to more than 30 km, have been used to compare the ray tracing model against real measurements [10]. In Fig. 10 both the measured and the modeled PPL and SEL can be seen. The acoustic effects of the increased depth in the range interval from approximately 5 km to 20 km are clearly visible in the plot with a significant drop in both SEL and PPL. It is also possible to see that the SEL follows $-10\log(r)$ in the region

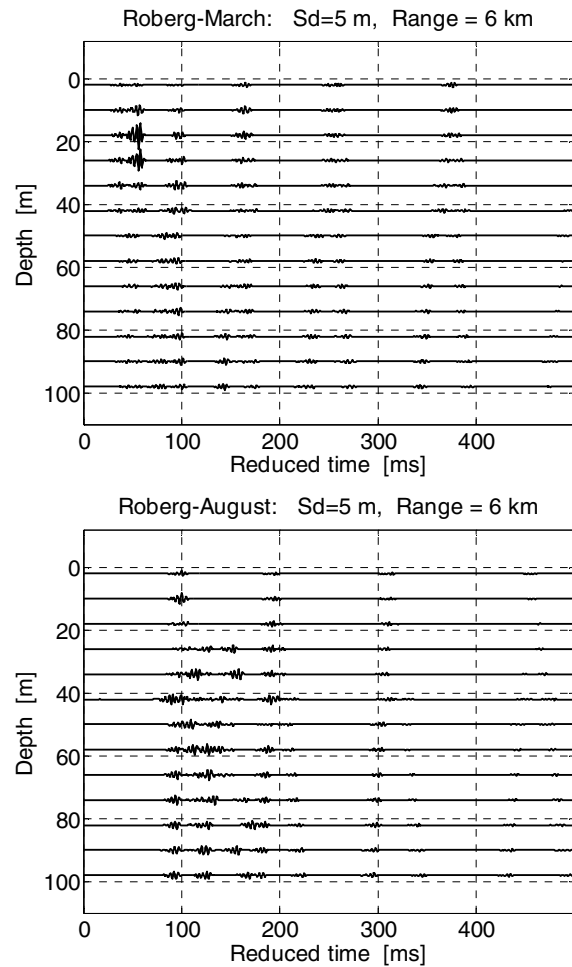
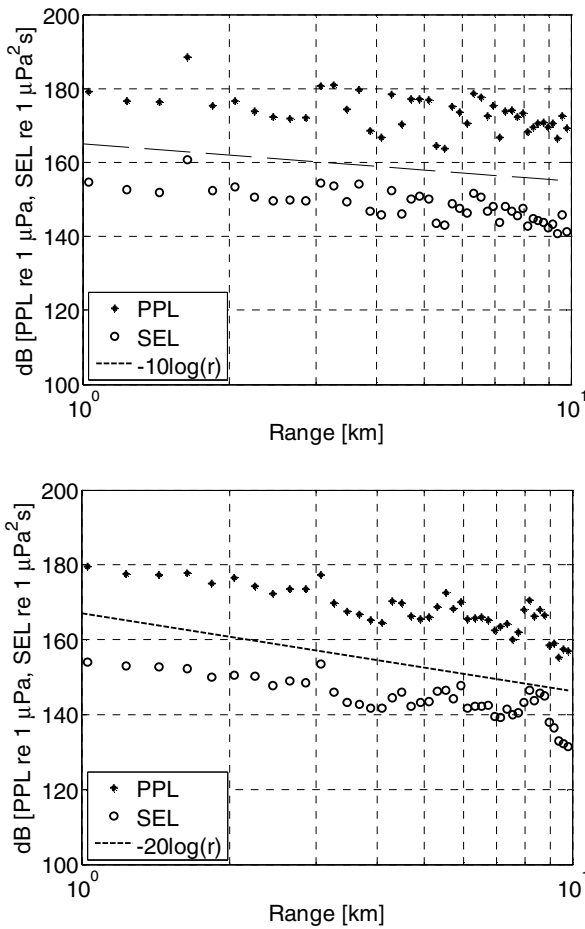


Figure 8. Left: PPL and SEL to receivers at 25 m depth as function of range. Right: Time responses received at depths from 0 m to 100 m at a range of 6 km from the source. Upper: Winter conditions with a strong surface channel with significant higher sound level than normal in the depths around 20 m Upper: Winter conditions. Lower: Summer conditions.

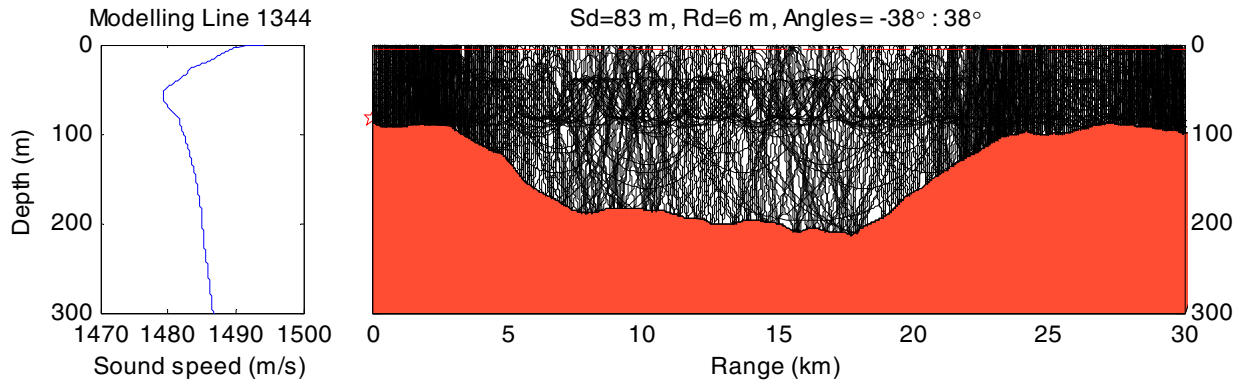


Figure 9. Ray traces in the case of up sloping and down sloping bottom. In both cases the depth changes with 150 m over a distance of 20 km, from 15 km to 35 km away from the source position. The sound speed in water is constant equal to 1500 m/s.

with relatively flat bathymetry (< 2-3 km) and then when the depth increases it approaches $-40\log(r)$. When the depth decreases again, around 20 km, the SEL returns to the $-10\log(r)$ asymptote. The drop around the deeper range can be explained by the Lloyd mirror effect mentioned above.

The modeled results also show this behavior, but the variations in levels are more pronounced. In real life caustics and cancelling effects does not occur to such extent as the idealized world of modeling. This is due to small variations in sound speed along the range from source to receiver and variations in bathymetry and sea surface.

In Fig. 11 the modeled time responses, together with the SEL and PPL measurements as function of depth can be seen. A very clear sound channeling effect can be found around 50 m depth. This sound channel will make the sound at this depth to reach much further range than normally. The variations in PPL and SEL as function of depth also show that the distribution of both peaks and energy varies a lot.

A. New TL Function

Based on the finding in the real measurements a new TL function is suggested. This function uses the depth as function of range as a correction factor to the already described TL function (1). The new TL function is written as:

$$TL = 10 \cdot \log_{10} \left(r^2 \left(1 + \frac{r^2}{r_t^2} \right)^{\frac{1}{2}} \right) + N \cdot \log_{10} \left(\frac{D(r)}{D_0} \right) \quad (3)$$

where N is a experimentally found constant and D_0 is a reference depth.

Using N equal 40 and the start depth, 83 m, as D_0 the TL becomes remarkable coincident with the measured results (see Fig. 12). It is not clear why $-40\log(D(r)/D_0)$ follows the measured results so good, but an approximation to the Lloyd mirror effect might be an explanation. The result is, however, dependent on the sound speed profile. A test done with constant sound speed profile showed a smaller drop at the

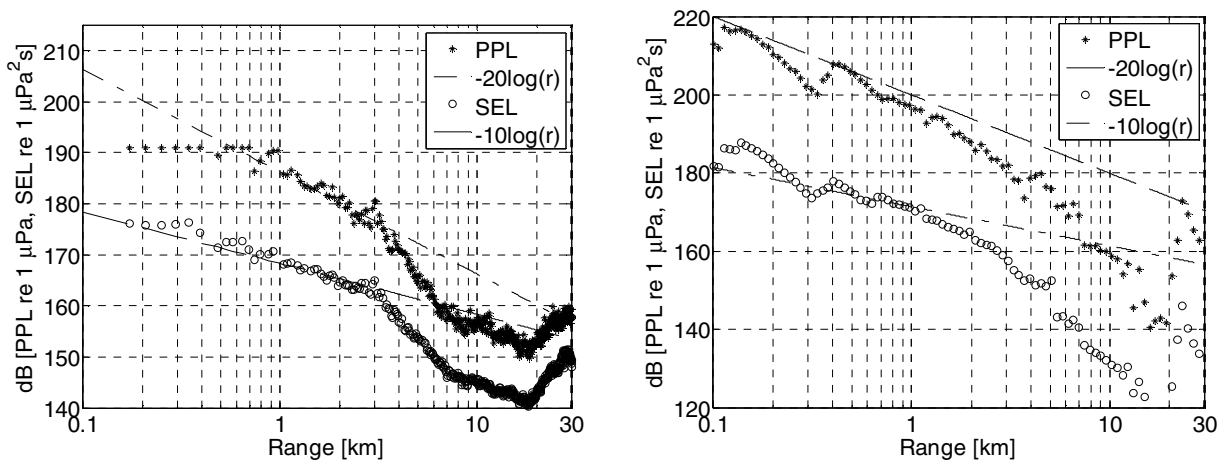


Figure 10. Measured (left) and modeled (right) peak and RMS levels from the field Nordland VII outside Vesterålen, Norway. It should be noticed that the measured signal was clipped at 191 dB. The values below 1 km should therefore be treated with care. Be aware that the scales are not the same between the two plots.

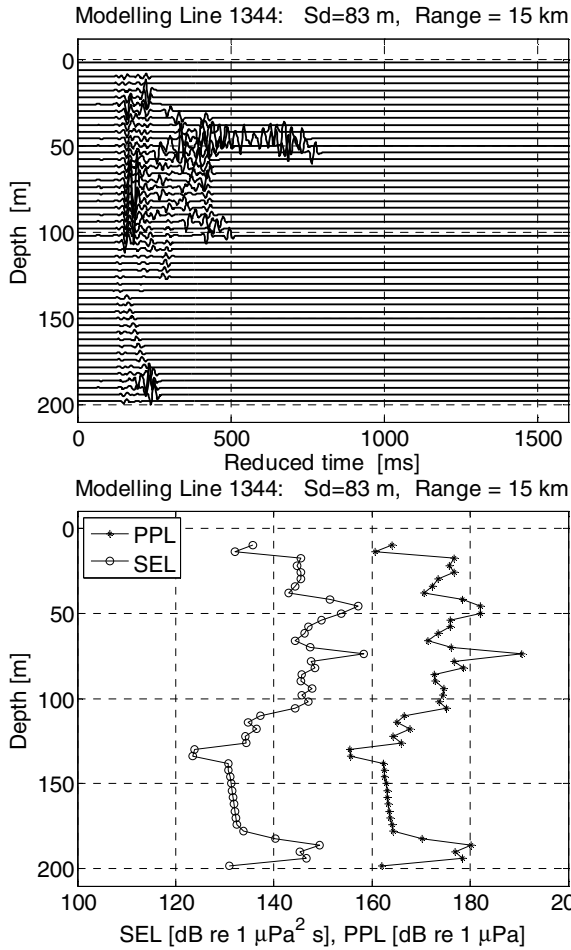


Figure 11. Upper: Time responses as function of depth. There is a clear sound channeling effect around 50 m depth. Lower: PPL and SEL for the time responses in the upper plot. There are large variations in both levels.

deeper regions suggesting that N in (3) might depend on the sound speed profile.

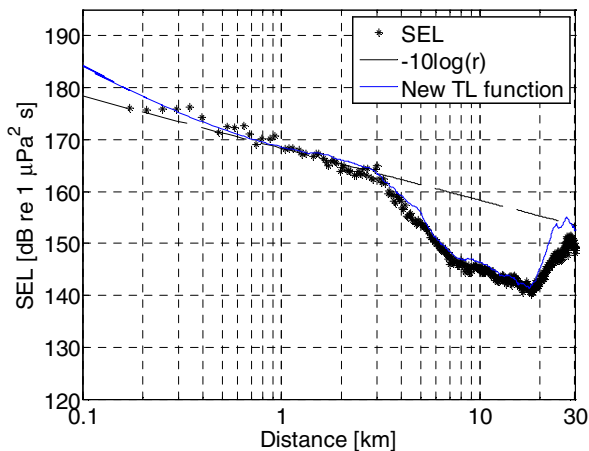


Figure 12. SEL of the measured timeresponses, together with $-10\log(r)$ and the new TL function described in the text.

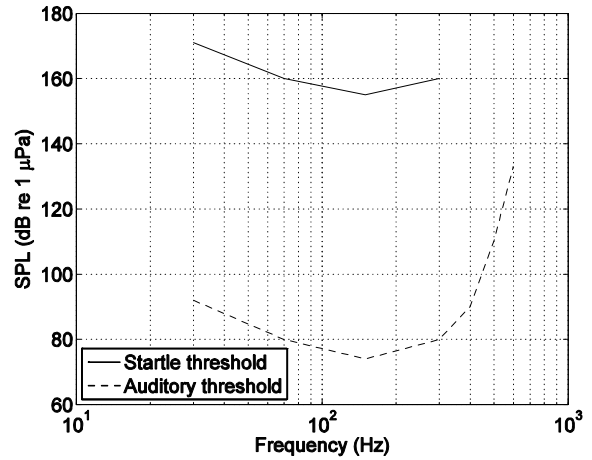


Figure 13. Auditory and startle threshold for Atlantic cod. Auditory threshold data taken from [11] and [12], startle threshold data are preliminary results from the University of Oslo (to be published).

B. Disturbance of Fish

The University of Oslo, Institute of Biology, has done measurements of startle threshold in different fish species. Atlantic cod has been among these and the sound thresholds for this fish can be seen in Fig. 13. Acoustical startle responses are strong and rapid escape reactions directed away from the sound source ([13], [14]).

By using the startle threshold (ST) it can be determined at how far distance, called critical distance, fish is disturbed by a sound. We define the critical distance in a given species of fish as the maximum distance where sound pressure level exceeds startle response threshold. This is an indicator of what distance the fish might be disturbed by a sound (see Fig. 14). It should be noticed that fish, and sea mammals, might show other behavioral changes at lower sound levels than those triggering startle response. The threshold for alarm responses has been observed at 20-25 dB lower sound levels than the threshold for startle responses [15].

By using the startle threshold in Fig. 13 the critical distance would be approximately 5 km for the real measurements. It must be pointed out that this result is just to show how an acoustical-biological model can be made, not a final conclusion.

V. CONCLUDING REMARKS

Even if spherical and cylindrical spreading, i.e. $-20\log(r)$ and $-10\log(r)$ respectively, can be sufficiently accurate for flat sea beds with constant sound speed, the real scenarios are rarely or never like this. There are always bathymetric and/or sound speed variations, variations that will affect the sound propagation. This paper has elucidated these variations by modeling different scenarios with a ray tracing computer model.

Changes in bathymetry, e.g. downslope and upslope as modeled in this paper, show that the distribution of the sound in the water depends on the water depth. This is intuitive since the amount of energy fed into the system by a source is spread over

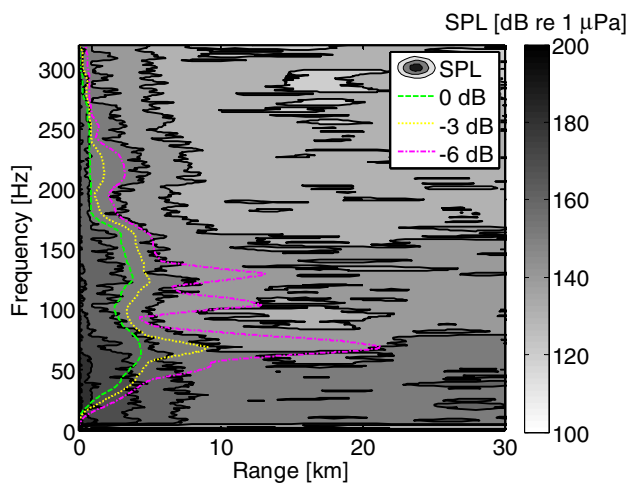


Figure 14. Illustration of an acoustic-biological model. The critical range is indicated by lines (-3 dB and -6dB shows how the critical range changes with changed startle threshold) as function of frequency.

a larger volume when the water depth increases, and *visa versa*. This change can be corrected for by introducing a correction term in the commonly used TL functions, including the depth information as function of range. This correction factor was also tested on a real measurement from a seismic survey done in Vesterålen, Norway, with remarkable coincidence.

This paper has also shown that rather small variations in bathymetry and/or sound speed can affect the sound propagation very much. Especially seasonal sound speed variations, such as those found in Norway for instance, will change the behavior of the propagating sound. It should also be noticed that in situations where the sound speed drops towards the surface, the sound channeling effect that occurs makes the bottom variations less significant for the sound propagation. The opposite occurs when the sound speed increases towards the surface. Then the sound is bent downward to the bottom, making any variations even more important.

As the sound propagation modeling tools become more sophisticated it is possible to create more realistic TL functions to predict noise impact under water. Such models can, if combined with good threshold data, be used to create an acoustical-biological model to predict how far away sea mammals can be affected by a sound event, e.g. seismic activity. There are, in Norway for instance, conflict of interests

between the petroleum and fishery industry, and good models can be used during the planning of seismic activity to minimize the negative effect sound exposure can have on fish and fishery.

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