CALCULATIONS FOR SCENARIO A1 WITH THE MSM CODE

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1 INTRODUCTION

This paper presents results of calculations for the scenario A1 "Orca vs. salmon" of the Weston Memorial Symposium laid out in the article of Ainslie and Zampolli[1] in this proceedings edition. The calculations were made along the guidelines of the scenario with an existing raytracing code called MSM (Minehunting simulation model) that was written for the design and analysis of minehunting sonar systems. In chapter 2 of this paper the MSM model is briefly described. Chapter 3 gives the results of the calculations which can be compared with those of Ainslie and Zampolli presented in their paper[1].

2 NUMERICAL APPROACH

2.1 The simulation model MSM

The calculations for the scenario A1 were made with the already existing sonar simulation model MSM which stands for minehunting simulation model". The model was developed by D. Kraus from the University of Applied Science Bremen for the design and analysis of minehunting sonar systems.

In the field of active sonar system simulation, the ray tracing approach is proven as the method of choice for sound propagation modelling for a variety of scenarios. This is especially true for mine hunting sonars since typical operating frequencies are rather high, so that the ray theory conditions are valid. The advantage of this method compared to other propagation models lies in its numerical efficiency. Especially mode based approaches require a large amount of computing time since the number of modes increase with frequency. In addition to the time factor, modelling of the transmission and reflection of sound at rough wave guide boundaries, as well as reverberation modelling is comparatively simple in the ray tracing method. For the ray tracing MSM uses an approach based on the dynamic ray tracing formalism developed by Cerveny[2] which was chosen for the elegance of the amplitude calculations compared to the standard formulation.

The MSM code has a modular design that allows the incorporation of different submodels for the simulation of the properties of the water (sound speed and absorption) and especially the interaction with the seafloor and the sea surface. The main model for both seafloor and sea surface scattering is a model published by the Applied Physics Laboratory of the University of Washington, usually known as APL-UW model[3] or Jackson model after the leading scientist involved. This model is based on physical assumptions for the interaction of sound with the seafloor and the surface and is widely accepted as a reliable approximation for high frequencies. The assumption for the source level spectrum of wind generated noise in the definition of the orca scenario is also taken from that model. Another model that can be used for the calculation of the interaction with the sea surface and bottom is the older SEARAY model from the Applied Research Laboratory of the University of Texas at Austin. In contrast to the APL-UW model this model is not based on physical models but on fits to a large number of scattering measurements. It is usually considered inferior to the APL-UW model although the differences between the model are relatively small in many cases.

A special focus of the MSM code lies on the reverberation calculation with the inclusion of bistatic reverberation. The model traces all paths up to the order of several reflections from sea surface and bottom and uses the paths for the evaluation of the bistatic scattering. For the calculation of the bistatic scattering strength the bistatic scattering model of Ellis and Crowe[4] is used. This model proposes an analytic function for the three-dimensional backscattering which has to be fitted to known results for angles where information exists. The parameters Lambert constant, facet strength and facet slope for the bistatic case are fitted with the results for the monostatic case calculated with the APL-UW model.

2.2 The scenario A1

An extensive description of the scenario A1 "Orca vs. salmon" can be found in the paper by Ainslie and Zampolli in this proceedings[1]. If not indicated otherwise the formulas in this section are taken for from the scenario definition in that paper and reproduced here for clarity only.

The basic setup describes an orca (*Orcinus orca*) hunting a chinook salmon. The orca is at a depth d_0 of 5 m and the salmon at a depth d_F of 25 m. The signal-to-noise ratio for the detection problem is to be investigated for slant ranges of up to 500 m. A deep water configuration is assumed, i.e. the influence of a seafloor in not included.

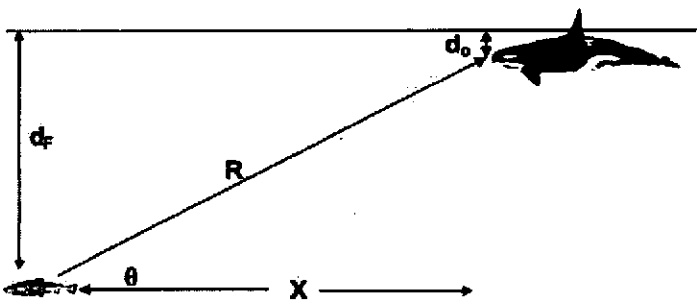


Figure 1: Illustration of orca v salmon geometry [reprinted from Au et al[5]]

Based on work by Foote[6] a target strength of –30 dB was chosen for the salmon. The orca transmits a broadband signal which is approximated by a Hann-shaded cosine pulse with 5 half cycles. The pulse shape to be considered is

$$p_{\mathrm{Tx}}(R,t)R = -A\, w_{\mathrm{Hann}}(t-R/c)\cos\left(2\pi f_0 (t-R/c)\right), \tag{1}$$

where

$$w_{\mathrm{Hann}}(t) = \begin{cases} 0 & t \le -T/2 \\ \cos^2\left(\pi \frac{t}{T}\right) & -T/2 < t < T/2 \\ 0 & t \ge T/2 \end{cases} \tag{2}$$

and T is the pulse duration for 5 half cycles

$$T = \frac{5}{2 f_0}$$

For the centre frequency of f_0= 50 kHz this gives a pulse duration of T = 50 μs.

The parameter A is the maximum amplitude of the product of distance with free field acoustic pressure It is set to 15 kPa in the scenario definition which leads to a peak-to-peak source level $\mathrm{SL}_{\mathrm{pp}}$ of approximately 209.5 dB re 1 μPa^2 m^2 according to the relationship

$$\mathrm{SL}_{\mathrm{PP}} \approx 10\log_{10}\frac{4A^2}{1\,\mu\mathrm{Pa}^2\mathrm{m}^2} \tag{3}$$

following Ainslie[1,7]. The source level definition in the MSM code is not based on the peak-to-peak pressure but on the effective value of the pressure. Therefore the input value for source level $\mathrm{SL}_{\mathrm{eff}}$ used for the calculations was assumed to be approximate 9 dB lower the paek-to-peak source level and a value of 200 dB re 1 μPa^2 m^2 was chosen.

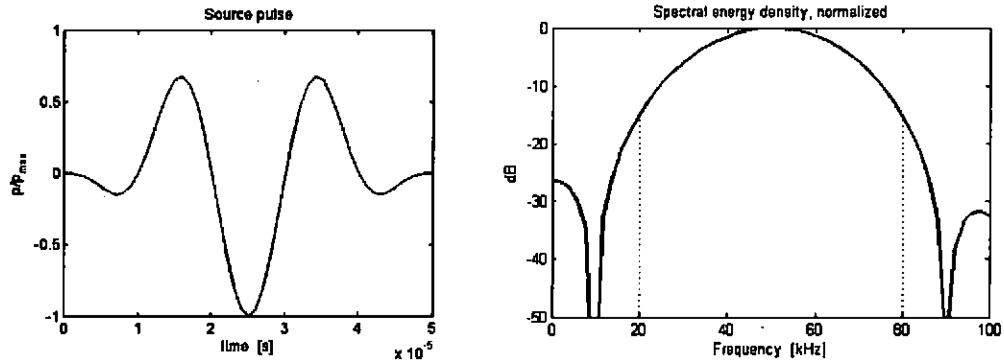


Figure 2: Orca source pulse in the time domain (left) and spectral density relative to the centre frequency f_0 = 50 kHz (right)

Figure 2 shows the orca's source pulse in the time domain with a duration of 50 µs and the spectral energy density of the pulse relative to the centre frequency of 50 kHz. For the calculations a bandwidth of 60 kHz between 20 kHz and 80 kHz has been assumed.

2.2.1 Beam pattern

For the orca sonar a baffled circular array is assumed as the transducer. The beampattern of an unshaded circular array is

$$b(u) = [2J_1(u)/u]^2, \tag{4}$$

where $J_1(u)$ is a first order Bessel function of the first kind and u is given as

$$u = (\pi Df / c)\sin\psi. \tag{5}$$

with frequency f, diameter D and angle ψ from the array's axis of symmetry. The resulting beam pattern for the diameter D = 10 cm the centre frequency of 50 kHz is shown in Figure 3.

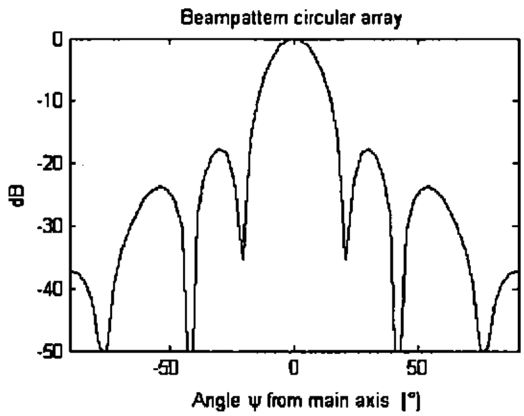


Figure 3: Orca beampattern for the centre frequency of 50 kHz

2.2.2 Noise calculation

According to the scenario definition the dominant noise source, and hence the only one to be considered, is wind noise from the surface. The APL-UW model gives a source level spectrum for wind generated noise in the case of air cooler than water of

$$\mathrm{SDSL} = 41.2 + 22.4\log_{10} V - 15.9\log_{10} F - \log_{10}\delta \quad \mathrm{dB\,re\,\mu Pa^2\ Hz^{-1}} \qquad (6)$$

where F is the frequency in kHz, V is the wind speed in m/s and δ=1.

SDSL is the dipole source level expressed as a spectral density per unit area of the sea surface. For small distances from the surface and negligible attenuation this leads to a noise spectral density level NSDL at the receiver that is approximately independent of the depth as

$$\mathrm{NSDL} \approx \mathrm{SDSL} + 10\log_{10}\pi = \mathrm{SDSL} + 4.971. \qquad (7)$$

In order to calculate the actual received spectral noise density N_f one has to integrate the angular noise contribution over the beampattern which gives

$$N_f(R) = \left(10^{\mathrm{SDSL}/10}\,\mu\mathrm{Pa}^2/\mathrm{Hz}\right)\int_{4\pi} b(u)\exp\left(-\frac{2\beta z}{\sin\theta_N}\right)\cos\theta_N\,\mathrm{d}\theta_N\,\mathrm{d}\phi, \qquad (8)$$

The spherical integration has to be carried out separately for each slant range R considered because it is assumed that the beam axis is always directed towards the salmon, which means that the relation of the angles in the argument u of the beampattern $b(u)$ and the integration angle θ_N varies with range. Effectively the integration has to be carried out over a half-sphere of θ_N = 90°...180° and ϕ = 0°...360° since the noise comes only from the surface. The beam axis is always depressed from the horizontal plane. Therefore the noise only enters through the sidelobes of the beampattern for small ranges and parts of the mainlobe for larger ranges but never through the full mainlobe.

Since for small ranges the animal mainly presents the back of it's head towards the surface the question of the backside of beampattern has to be addressed. Without further knowledge about the animals auditory system there are two assumptions that can be taken; either a completely baffled sonar or a sonar with a constant value of front-back suppression. In the first case it is assumed that no noise components from the surface are introduced through the backside of the head into the auditory system and in the second case the beam pattern on the backside is similar to the one on the front, only damped by a given amount by the tissue the sound travels through. If not indicated otherwise for all following calculations a value of front-back suppression of -40 dB was chosen.

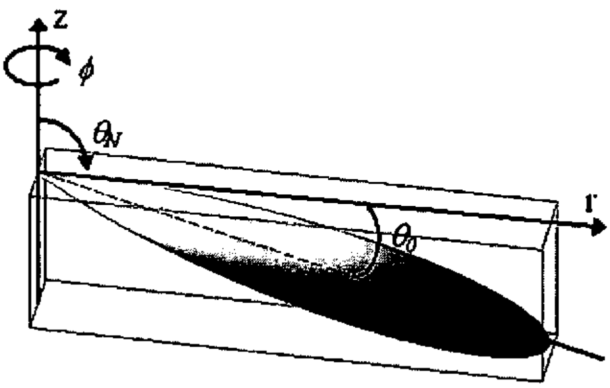


Figure 4: Sketch of the orca's beam and the spherical integration over the azimuth angle ϕ and the elevation angle θ_N. The grazing angle is labeled θ_0.

The actual integration was carried out by first transforming the beam pattern from spherical to cartesian coordinates, then rotating the beam to the grazing angle θ_0 that directs towards the fish for the given range R and afterwards transforming the beam back to spherical coordinates for the integration over the angles ϕ and θ_N.

The in-beam noise level IBNL is obtained from equation 8 by integration over frequency and conversion to decibels

$$\mathrm{IBNL}(R) = 10\log_{10}\left(\frac{\int N_f(R)\mathrm{d}f}{1\,\mu\mathrm{Pa}^2}\right). \tag{9}$$

The signal-to-noise ratio is defined as the ratio of the in-beam sound level IBSL and the in-beam noise level IBNL. As an approximation for the IBSL the echo level (EL) is taken, which is defined as the maximum value of the received sound pressure level squared, averaged over the receiver integration time t_{Rx}, i.e.,

$$\mathrm{EL}(R) = 10\log_{10}\max\left[\frac{1}{t_{\mathrm{Rx}}}\int_{t_{\mathrm{Rx}}}\frac{p^2(R,t)}{1\,\mu\mathrm{Pa}^2}\mathrm{d}t\right], \tag{10}$$

Since the raytracing code MSM works strictly in the frequency domain, the integration over time over the received signal cannot be performed properly. As a substitute, the echo level EL_f provided by the standard frequency domain sonar equation from the values of source level (SL), frequency dependent transmission loss (TL_f) and target strength (TS)

$$EL_f = SL - 2\,TL_f + TS$$

is taken and integrated similarly to the integration of the noise level in equation 9.

$$\mathrm{EL}(R) \approx 10\log_{10}\left(\frac{\int 10^{EL_f(R)/10}\,\mathrm{d}f}{1\,\mu\mathrm{Pa}^2}\right) \tag{11}$$

3 RESULTS

This chapter gives the results of the calculations for scenario A1. It is divided into the results of the directional noise calculations according to chapter 2.2.2, results of calculations for single ranges and the overall results of the beam aimed towards the fish for all ranges.

3.1 Noise calculations

The important quantity for the calculation of the signal to noise ratio in this scenario is the in-beam noise level IBNL according to equation 9. It is significantly lower than the noise level NL that would be calculated without the spatial integration over the directed beam simply as

$$\mathrm{NL}(R) = 10\log_{10}\left(\frac{\int 10^{NDSL(f)/10}\,\mathrm{d}f}{1\,\mu\mathrm{Pa}^2}\right) \tag{12}$$

Contrary to the in-beam noise level this quantity is independent of range and grazing angle. Figure 5 shows both noise measures for wind speeds of 2 m/s, 6 m/s and 10 m/s. For the calculations a front-back suppression of –40 dB was assumed. It is apparent that the directed IBNL is always much lower than the non-directional noise level NL. This is due to the fact that the beam pattern according to equation 8 blanks out the main part of the noise from the surface. The beam is always slanted away from the surface, more for short ranges and, accordingly, high grazing angles than for large ranges and low grazing angles.

The difference between these two noise measures can be interpreted as array gain (AG), the suppression of the noise gained by integrating over the beam pattern. Figure 6 shows the array gain both for a completely baffled sonar and sonars with front-back suppression ratios of –40 dB and –30 dB. For all configurations the ray gain drops off with increasing range, except for the small dent for very small range for the sonar with –30 dB front-back suppression.

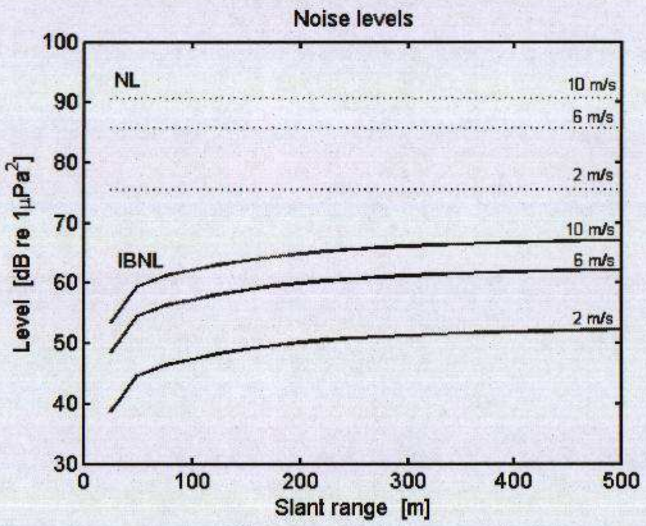


Figure 5: Comparison of in-beam noise level IBNL for the beam directed towards the fish (solid lines) and noise level NL without consideration of the beam pattern (dotted lines) for wind speeds of 2 m/s, 6 m/s and 10 m/s.

It can be seen that the difference between the sonar with 40 dB front-back suppression almost behaves like the completely baffled one, whereas the sonar with –30 dB suppression has an array gain that is around 1 dB lower than the other ones. For the sonar with 40 dB front-back suppression the array gain starts with a value of 38.6 dB at a slant range of 20 m where the fish is situated directly below the orca. The completely baffled sonar would have an infinite array gain at that point. In practice noise contributions from other sources would dominate at those ranges and limit the array gain. In all cases the array gain would reach a theoretical limit of 21.7 dB at infinite range where the beam would be horizontal and pick up noise through half it's pattern.

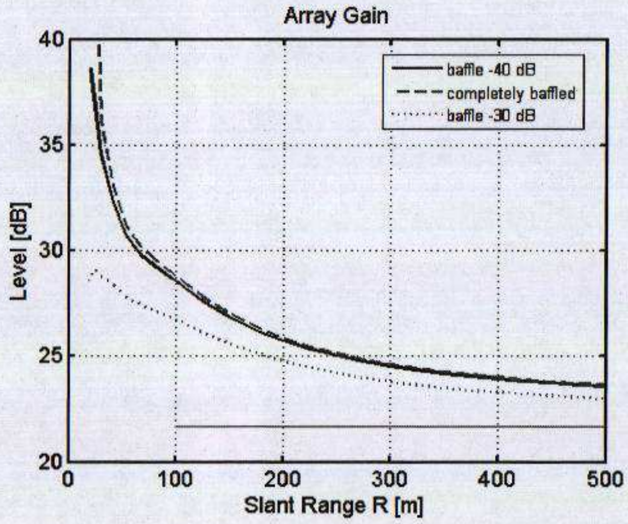


Figure 6: Array gain of the orca calculated as the difference between IBNL and NL for a completely baffled sonar (dashed) and sonars with front-back suppression ratios of –40 dB and –30 dB (dotted). The limit for infinite range is marked by a line at 21.7 dB

3.2 Single range calculations

Since the beam of the orca is always directed towards the fish it has a different grazing angle for each range value. Therefore both the calculations for the in-beam noise level and for the echo level have to be performed separately for each range. The following figures 7 to 9 show the results for the slant ranges of 100 m, 200 m and 500 m as graphic representations of the echo level and the signal to noise ratio for all depth values from the surface to 30 m.

For the noise calculations a wind speed of 2 m/s was chosen. The assumed position of the fish is marked with a black star in the diagram for 100 m and 200 m and a white star for 500 m. The orca is at a depth of 5 m. For the assumed geometry the slant ranges are almost identical with the ground ranges. It can be observed that although the beam is directed towards the fish the maximum echo level and SNR for the depth of 25 m is not at the position of the fish but considerably close to the orca. This is due to the lower slant range for those positions which counteracts the lower intensity from the beam pattern for the respective rays. This effect increases with increasing range. The pictures for ranges greater than 100 m differ very little from each other because the change in grazing angle is already small for those ranges.

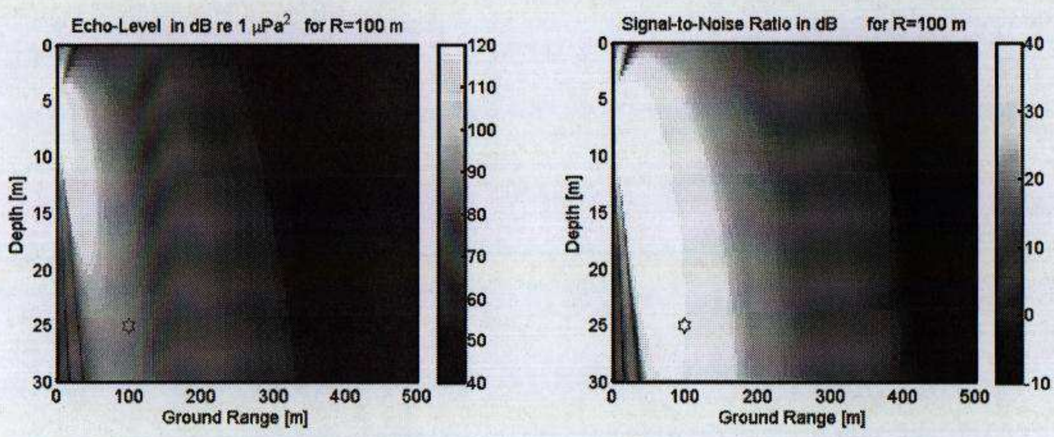


Figure 7: Echo level (left) and signal to noise ratio (right) for the slant range of 100 m (grazing angle 11.5°) The star marks the assumed position of the fish.

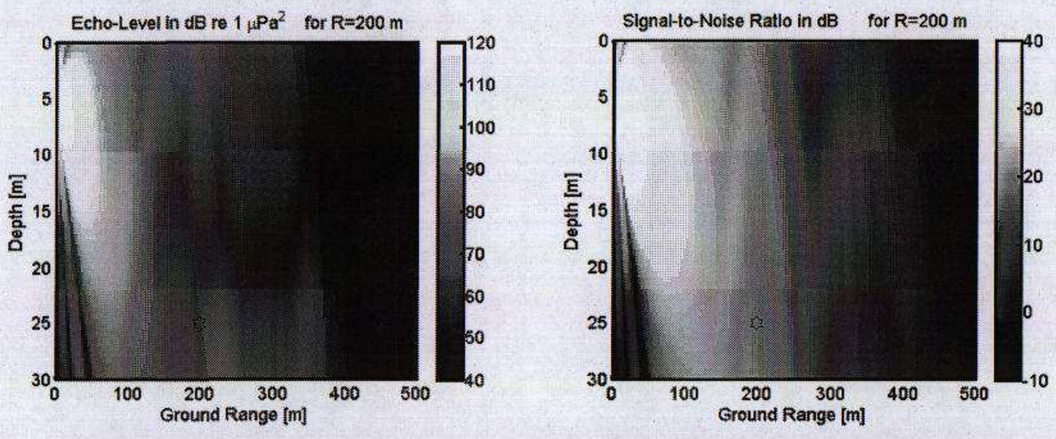


Figure 8: Echo level (left) and signal to noise ratio (right) for the slant range of 200 m, (grazing angle 5.7°) The star marks the assumed position of the fish.

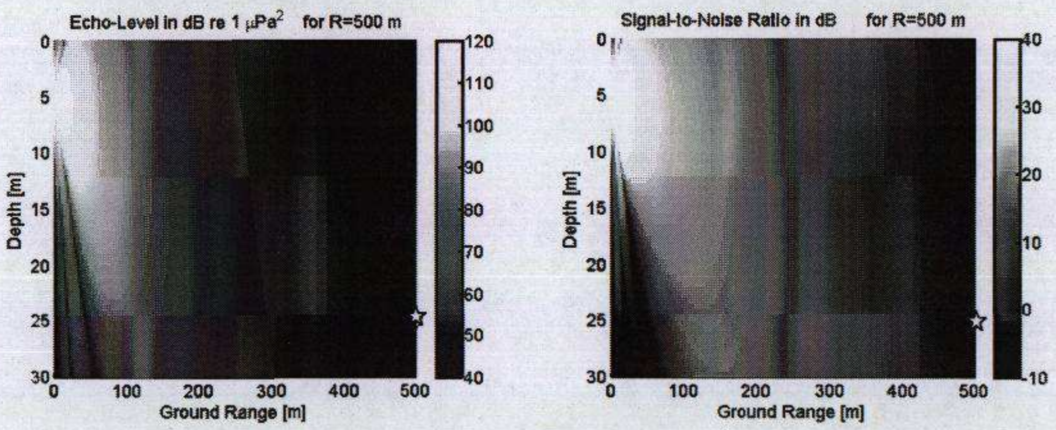
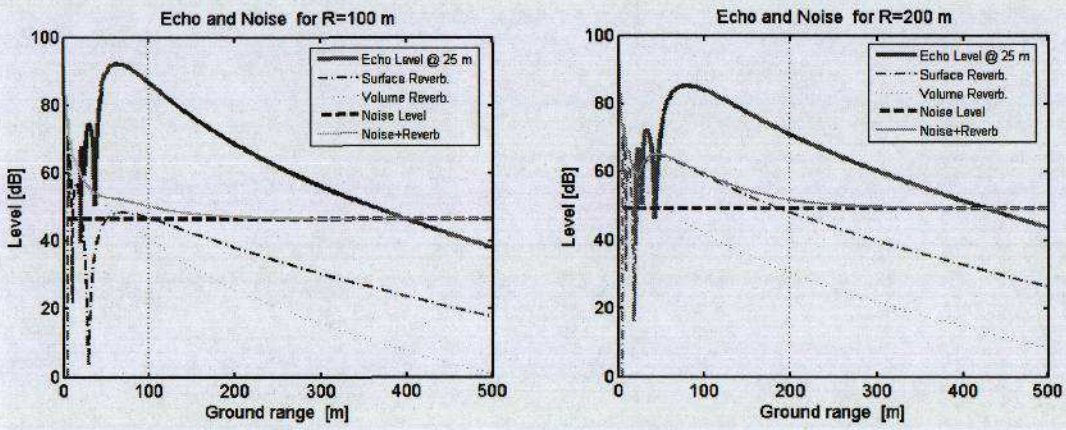


Figure 9: Echo level (left) and signal to noise ratio (right) for the slant range of 500 m (grazing angle 2.3°) The star marks the assumed position of the fish.

Figure 10 shows a comparison of the calculated values of echo level, noise level, surface and volume reverberation and the sum of noise and reverberation for at the assumed depth of the fish of 25 m. The position of the fish is marked by a dotted vertical line for the ranges of 100 m and 200 m. It is apparent that the problem is dominated by wind noise rather than reverberation already for the low wind speed of 2 m/s.



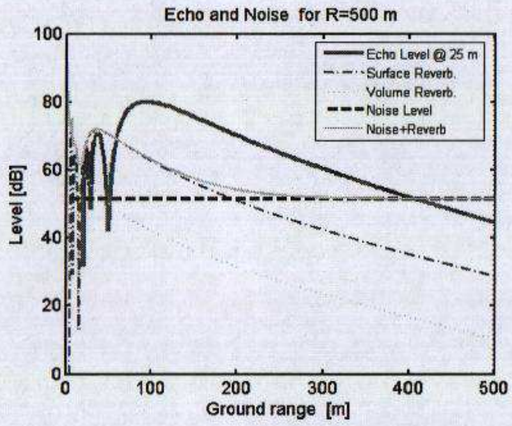


Figure 10: Echo level, noise level, reverberation, and the sum of noise and reverberation at the fish's depth of 25m and slant ranges of 100 m (top left), 200 m (top right) and 500 m(bottom).

Figure 11 shows the ratio of the echo level to the sum of all noise and reverberation terms (called background level) for the ranges considered. The assumed position of the fish is marked by filled diamonds on the curves.

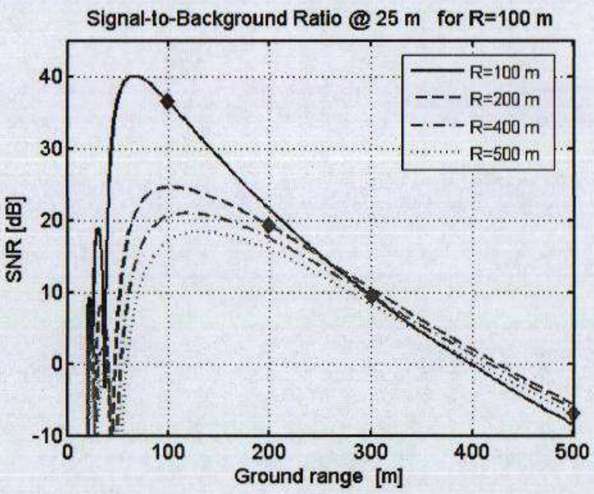


Figure 11: Signal to background (noise+reverberation) ratios for slant ranges of 100 m, 200 m, 300 m and 500 m.

3.3 Directed beam

Figure 11 already leads to the way to the combined results for the directed beam which is compiled from calculations for more ranges and grazing angles. Figures 12 and 13 show the results for wind speeds of 2 m/s, 6 m/s and 10 m/s. Echo level, noise level, reverberation from the surface and the water column and the sum of all noise and reverberation terms are depicted. Figure 12 clearly shows that already at a wind speed of 2 m/s the noise dominates the reverberation except for very short ranges where the beam is directed downwards at steep angles. This is even more so at higher wind speeds which can be seen in figure 13.

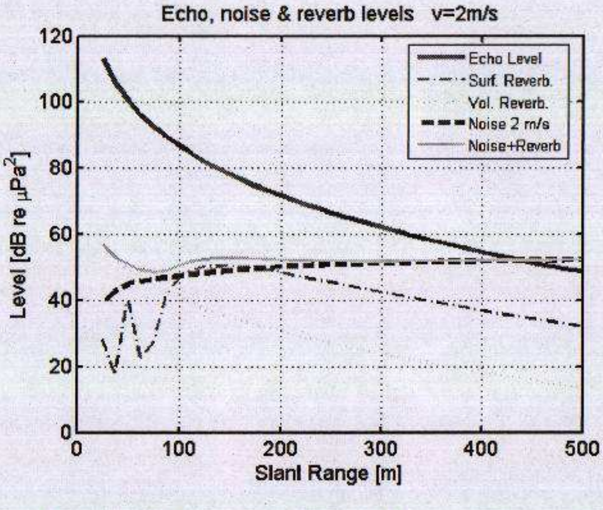


Figure 12: Echo level, noise level (IBNL) for a wind speed of 2 m/s, surface and volume reverberation and the sum of noise and reverberation at the fish's depth of 25m for the directed beam and slant ranges from 25 m to 500 m.

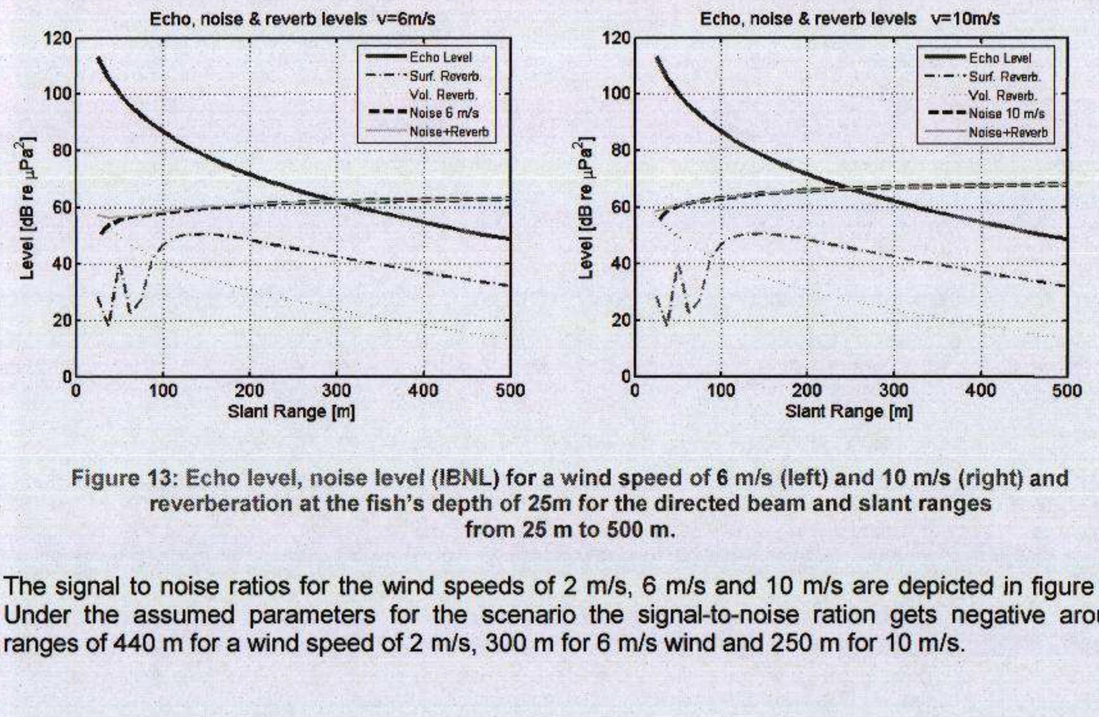


Figure 13: Echo level, noise level (IBNL) for a wind speed of 6 m/s (left) and 10 m/s (right) and reverberation at the fish's depth of 25m for the directed beam and slant ranges from 25 m to 500 m.

The signal to noise ratios for the wind speeds of 2 m/s, 6 m/s and 10 m/s are depicted in figure 14. Under the assumed parameters for the scenario the signal-to-noise ration gets negative around ranges of 440 m for a wind speed of 2 m/s, 300 m for 6 m/s wind and 250 m for 10 m/s.

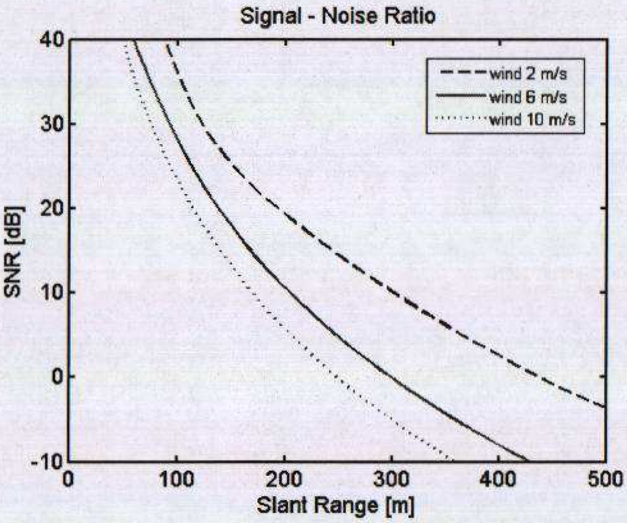


Figure 14: Signal to noise ratios for wind speeds of 2 m/s, 6 m/s and 10 m/s

The raytracing calculations also give values for the transmission loss of the orca's sonar signal. The MSM code itself only gives results for single frequencies, i.e. the narrowband transmission loss. These results are shown in figure 15 as a two-dimensional graphic representation of transmission loss versus slant range and frequency on the left hand side and for the distinct values of 20 kHz, 50 kHz and 80 kHz on the right hand side. As one expects, the transmission loss increases with increasing frequency due to the higher absorption coefficient for high frequencies.

From the narrowband transmission loss values a broadband value can be calculated by integration over the frequency range taking into account the relative spectral content of the signal. The results of this calculation is shown in figure 16 as the difference to the narrowband transmission loss at the centre frequency of 50 kHz. It has to be noted that this approach did not take into account the fact that for this two-way problem the transmission loss is not symmetric, i.e. the transmission loss in the direction from the salmon back to the orca is different from the one in the other direction. The reason for this phenomenon is that the reflected signal has a different frequency content than the original one. The high frequency content has been damped stronger on the way to the salmon than the low frequency content. This effect has been included in the calculations by Ainslie and Zampolli in reference[1] .

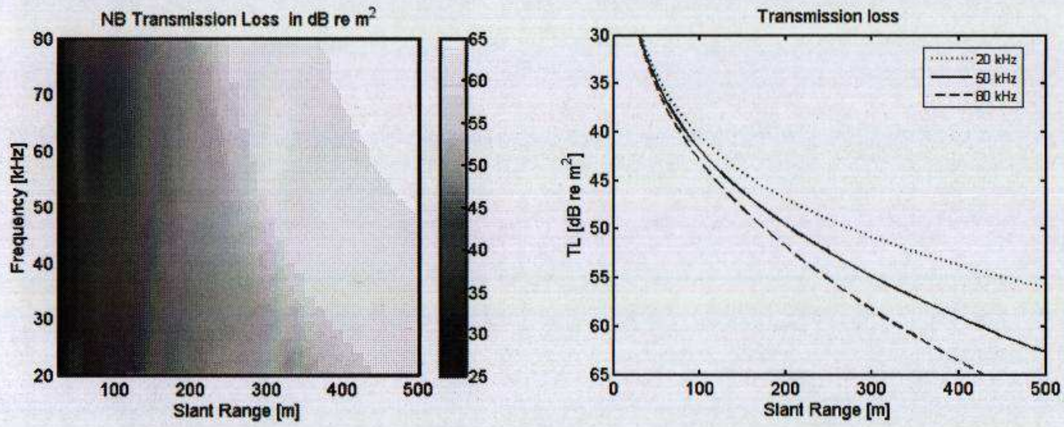


Figure 15: Narrowband transmission loss for the frequency range of the orca's signal.

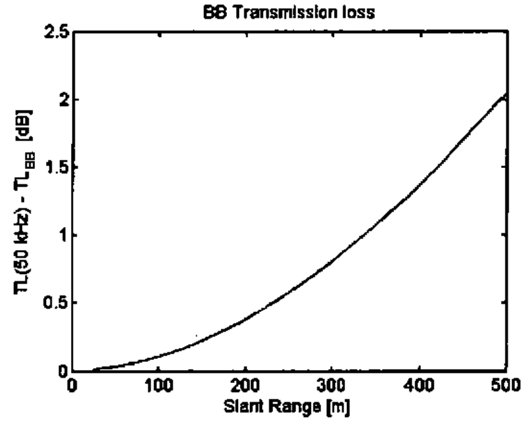


Figure 16: Broad band transmission loss as difference to the transmission loss of the centre frequency f=50 kHz.

4 SUMMARY

Calculations for the scenario A1 "orca vs. Chinook salmon" of the David Weston memorial symposium with the sonar performance modelling code MSM were presented. The propagation modelling of the code is based on dynamic ray tracing. For the noise and reverberation modelling the APL-UW model was used. The noise was generated by wind on the sea surface. The calculations show that the noise received by the orca is greatly reduced compared to the omnidirectional noise level at the position of the orca due to beamforming with a thin beam. Nevertheless is the detection, even at low wind speeds, mainly limited by noise and not by reverberation for the parameters of the scenario.

5 REFERENCES

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