ESTIMATING RANGE DEPENDENT SEDIMENT THICKNESS AND REFLECTION COEFFICIENTS FROM BATHYMETRIC DATA FOR IMPROVED SONAR PERFORMANCE MODELLING

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Abstract: *Knowledge about the underwater environment is critical to anti-submarine warfare operations in littoral waters. The sonar settings and depth selections can significantly affect the predicted sonar performance. Bathymetry and sound speed profiles can be found or measured on site, whereas the geoacoustic properties of the seabed usually rely on sporadic historical data. Sediment thickness is important for low- to-mid-frequency active sonars, which cannot be found in the traditional sediment databases where only the top layer is sampled. The thickness of sediment deposit in an area will, among other things, depend on the shearing angle of the sediment and the slope of the bottom profile. Utilising available environmental information, such as granular size and bathymetry, an estimate of geoacoustic properties along the bottom profile can be made. When using a sonar performance model, a reflection coefficient for the bottom interface is required. The reflection coefficient is frequency-dependent and depends on the substructure of the bottom. The available information is utilised in a simple and fast calculation which gives the environmental parameters along a bottom profile to be used in a sonar performance model. The goal is to improve the accuracy of the predicted sonar ranges without making extensive measurements of the sea floor. We find that there seems to be a strong correlation between the slope of the sea bottom and the sediment thickness in the area of the North Sea west of Marstein. Furthermore, the background level towards the Norwegian coast is modelled, using a range dependent sediment profile, and compared to sonar data from the same region. Finally, the modelled background level with a range dependent sediment profile is compared to previous models with range independent sediment profiles.*

Keywords: *Sonar, Modelling, Sound propagation, Bathymetry, Sediments*

1. INTRODUCTION

In underwater acoustics, environmental control is a key factor in producing realistic simulations and predictions. During anti-submarine warfare (ASW) operations, only a limited time is available for data collection and model fitting, but a necessity for sound propagation modelling in realistic prediction of sonar ranges at various settings. Other than weather data and sound speed measurements, a rough dataset with measured depths in the area and a basic knowledge of the most common/probable sediment(s) is all the environmental information that can be assumed to be available.

Measurements of sediment properties and thickness have been extensively conducted in the North Sea along with backscatter and various other experiments. Some of this data was used in [1], where they, among other things, investigated the relationship between grain size in the sediment and its acoustic classification. Although there appears to be no correlation between the backscatter from a sediment layer and its grain size, there are studies of the correlation between grain size and critical friction angle of sand and soil [2],[3]. Without the knowledge of the critical friction angle of various sediments, the next best thing would be to compare the slope of the bottom to the thickness of the sediment layer. A correlation here will mean it can be possible to estimate the sediment thickness solely from knowing the bottom structures and a general knowledge about the seabed in the area.

For sonars operating in the low- to-mid-frequency range, the thickness of the sediment layer can play a vital role as the sound can be transmitted through the sediment layer and be reflected by harder subcrop, resulting in lower bottom loss [4]. In the littoral waters of the North Sea, the upper and underlying layers are Holocene marine sediments and Quaternary sediments respectively [1]. By estimating the slopes at which the sonar would see the subcrop, improved sound propagation modelling would be possible, especially in the complex environment towards the coast, without the need for costly and time consuming measurements. Furthermore, such a result could be utilised in other areas where the sediment properties are similar but only the depth profiles are available.

2. DATA

An area in the North Sea, west of Marstein, has been thoroughly mapped by the Norwegian Defence Research Establishment (FFI) between 2003 and 2008. In a geophysical survey, in September 2005 and February 2006, a parametric Kongsberg Maritime Topas PS 018 sonar, transmitting a 20ms 2-4kHz chirp pulse, and high resolution seismic equipment, two 40in^3 with single channel streamer, were utilised to map the Quaternary layer sequence. These sediment data were acquired on a coarse survey grid with a total track length of approximately 2500km, along with 39 sonobuoy drops which gathered wide-angle seismic data.

In addition to the sediment thickness dataset we used a 60m resolution bottom depth map from the same North Sea region, gathered in the same time period. The multibeam echosounder used to map the area was a 95kHz Kongsberg Maritime EM 1002 which has 111 beams and a $2^o \times 2^o$ 3dB beamwidth [1]. Both the bathymetry map and the sediment thickness data can be seen in Fig. 1, where the outline of the sediment thickness data is shown in red on the depth data in the left panel. The right panel shows the sediment data.

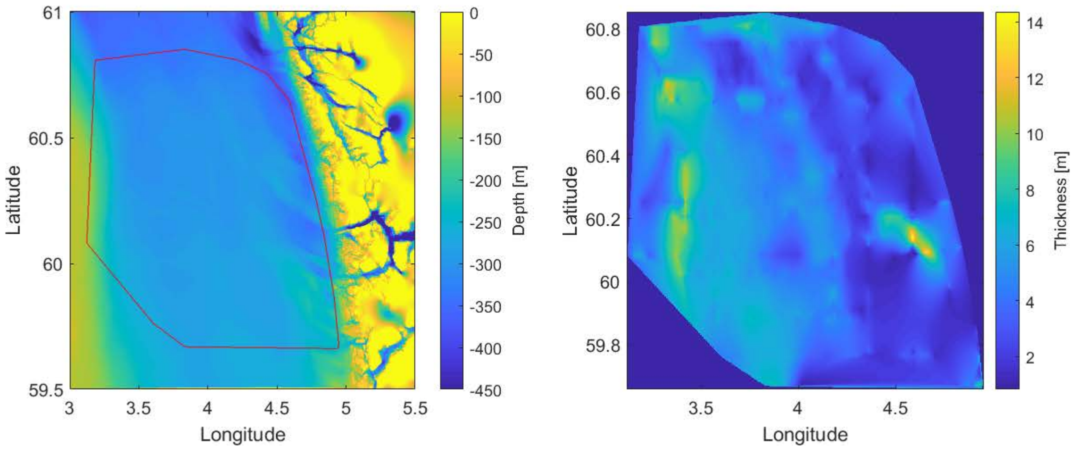

Fig.1: The bottom depth data, left panel, with the outline of area of the sediment data (red). The right panel contains the sediment data.

Finally, an experiment from the New Array Technology 3 (NAT3) program, Clutter Experiment 2 (CEX02), was used for testing and validation of the method. The NAT3 program was a joint collaboration between Thales Underwater Systems, TNO, FFI, and the French, Dutch, and Norwegian navies, where several experiments were conducted. One of the experiments, CEX02, was conducted in the Norwegian Trench in September 2002 with an active low-frequency towed array sonar system towed by FFIs research vessel, H. U. Sverdrup II. The receiver array consisted of equally spaced triplet hydrophones, while a towed body, the TNO Socrates source, transmitted a two second long hyperbolic, frequency modulated pulse every 90 seconds for two hours (79 transmissions). The received hydrophone data were processed up to a pre-tracking level following the steps in [5].

3. METHOD

Correlation of the sediment thickness with the bottom slope is sensitive to the resolution of the two maps. High resolution depth data results in a very uneven bottom with steep slopes on scales smaller than can be seen in the sediment map. In our case, the depth map has a resolution of 60m, while the sediment map is only at roughly 200m, meaning that the first step is to downscale the bottom map to roughly 20m resolution. Furthermore, the position, in latitude and longitude, of every data point in the sediment map is extracted and interpolated onto the downscaled depth map where the total slope of the position can be calculated. This result in a sediment thickness to bottom slope correlation which can be used to fit a function which best describes the relationship between the bottom slope and sediment thickness of this area. Because of the very high density of samples at minor slope angles compared to steeper slopes, the function fitting was done in an iterative process. First the fitting was done with all samples, which gives a very highly correlating fit for low slope angles. This was used to set the starting point (A) of an exponential decay function,

$$Y = Ae^{\lambda x}, \tag{1}$$

where Y is the sediment thickness, A is the sediment thickness at 0^{o} slope, λ is the decay factor, and x is the slope in degrees, before fitting the rest of the function to the mean sediment thickness in bins of increasing bin size for steeper slope angles. The increasing bin size is also to account for the lack of data at steep angles and the possibility of bins with a single sample contributing heavily to the fitting. This iterative fitting process gives an exponential decay function which performs well at both low slope angles, where there is a lot of data, and towards steeper slope angles, with sparse data sampling.

Finally, this function can be used along with the CEX02 dataset, to estimate the sediment thickness towards the shore in a detailed bottom profile in order to improve on the sound propagation models for this experiment. The function for estimating the sediment thickness in terms of the slope of the bottom surface is used to determine a slope limit where the sediment becomes acoustically transparent. The slope limit is determined by a qualitative assessment of reflection coefficient for a simple 3-layer environment, water-sediment-bedrock, easily computed by the OASES code [6], [7]. This allows us to simplify the bottom model and treat it as a uniform half-space composed of sediment or bedrock. The bottom loss as a function of grazing angle is calculated using an analytical expression for the Rayleigh reflection coefficient [8]. The background level will be modelled with two different sediment profiles, one range independent, seeing only the upper sediment layer, and one range dependent, varying between the upper sediment layer and the bedrock, depending on the slope of the profile. The physical parameters for the upper sediment layer (Holocene) and Quaternary/ bedrock layer is presented in Table 1. The geoacoustic properties of the bedrock are assumed to be similar to mudstone [9]. The acoustic model was compared to measured background levels in CEX02 similar to the work done in [10], where a range independent bottom loss model was used. The acoustic propagation model used is the acoustic raytracer Lybin [11].

Parameter	Value
Holocene	
Lambert's coefficient, μ (dB)	-18
Sound speed, c_{sed} (m/s)	1505
Density, ρ_{sed} (kg/m^3)	1.5
Attenuation, α_{sed} (dB/λ)	0.15
Quaternary/ bedrock	
Lambert's coefficient, μ (dB)	-18
Sound speed, c_{sed} (m/s)	2050
Density, ρ_{sed} (kg/m^3)	1.5
Attenuation, α_{sed} (dB/λ)	0.15

Table 1: Environmental parameters

4. RESULTS

A bottom profile with a cross section that displays a decrease in depth along the profile is shown in Fig. 2, along with the sediment thickness along the profile. The resolution along the x-axis is roughly 200m, and the profiles clearly show a decrease in sediment thickness for an increasingly inclined slope. The largest sediment thickness, of 10.46m, is found at roughly 15000m, where the slope is 0.14^o, whereas, the minimum sediment thickness, of 3.38m, is seen at approximately 22700m, with a slope of almost 0.6^o.

Figure 3 displays a density plot of all sediment thickness data and the corresponding slope at that location. The raw data indicates a clear correlation between an increase in slope resulting in a decrease of sediment thickness, which is only enhanced by the black stars which mark the weighted bin values. Furthermore, we see, in purple, the solid line marking the iterative exponential decay fit, which was locked to a starting position of 4.6m sediment thickness at 0^o slope by fitting all data points before fitting the decay of the curve to the weighted bin values. The dashed lines represent a fit of the 75 and 25 percentile of the binned data. These curves will all tend towards zero at steeper slopes if extrapolated.

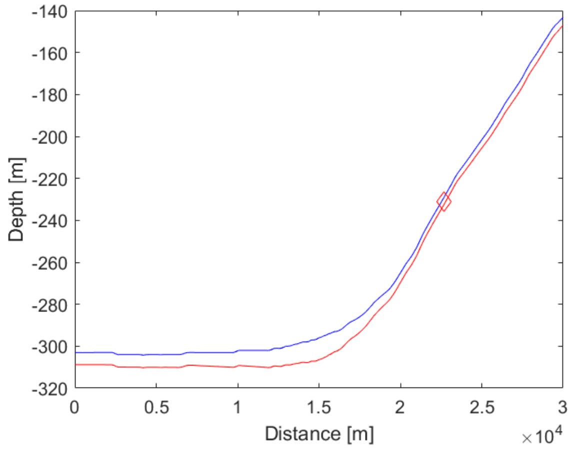

Fig.2: Depth profile in the North Sea (blue) along with a sediment thickness profile (red). The point with the thinnest sediment thickness is marked with a red diamond.

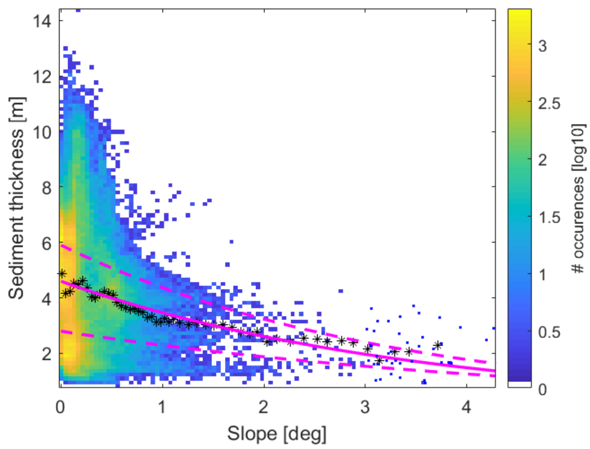

Fig.3: A density map of the relationship between bottom slope and sediment thickness. The average of different bins are shown as black stars, while the iterative exponential decay fit is shown as a purple solid line. The two dashed lines mark the exponential decay fit of the 75 and 25 percentiles of the bins.

Utilising the fitting parameters from Fig. 3, an acoustic propagation analysis based on the CEX02 data can be performed with an estimated sediment thickness for a given slope on the bottom profile. A comparison of measured and modelled background levels, for range independent and range dependent bottom loss models are shown in Fig. 4. The models compares well with the measurements the first 6km where the bottom profile is relatively flat. At greater ranges the models underestimates the background levels most likely due to increased backscattering not accounted for in the model. In Fig. 5 we see a statistical comparison of the CEX02 modelled and measured reverberation level analysis done with a range independent bottom loss model, as done in [10], and with a range dependent bottom loss model, in the left and right panel, respectively. The figures show a clear discrepancy between the two bottom loss models, with the range independent bottom loss model displaying a stronger correlation with measured reverberation level data compared to a range dependent bottom loss model, correlating the slope with sediment thickness. Surprisingly, the range dependent bottom loss model overestimates the reverberation levels for ranges greater than 10km, ranges at which our model predicts a thin to non-existing sediment layer, and show significantly greater spread in the error distribution at same ranges. The error is defined as

$$e_{RL} = BL - RNL, \quad (2)$$

where *BL* is the measured background level and *RNL* is the modelled reverberation and noise level.

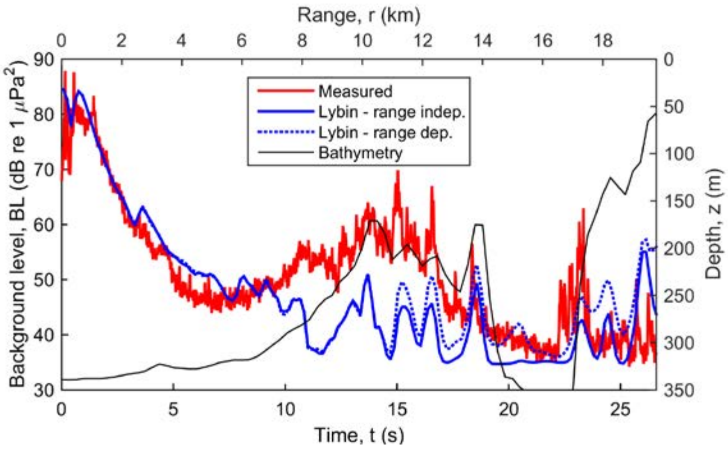

Fig. 4: Comparison of modelled and simulated background level in a beam directed towards the coast. The bottom profile is included as a visual guide.

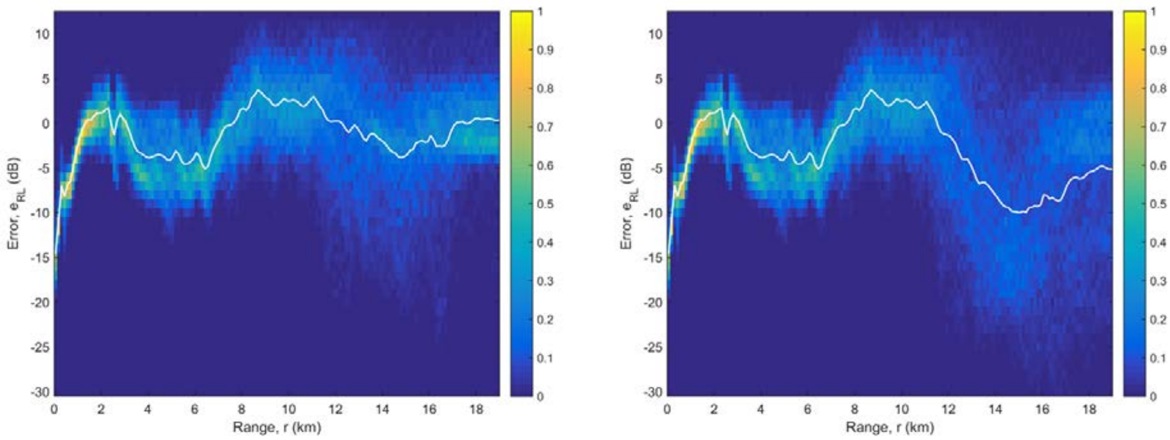

Fig.5: Normalised error distribution (in dB) for reverberation estimates with Lybin as a function of range. A range independent bottom loss model is utilised in the left panel, while a range dependent bottom loss model, correlating the slope with sediment thickness is utilised in the right panel. The white line represents the average error.

5. DISCUSSION

From the initial investigation based on the visual correlation from Fig. 2, it seems natural that for an increase in slope we see a decrease in the sediment thickness. However, the looks in Fig. 2 is extremely deceiving, with a variation in depth, y-axis, of 150 meters, while the variation in distance, x-axis, is 30 000 meters. This means that what seems like an extreme incline, actually is a slowly increasing slope over several thousand meters. This becomes apparent when finding that the maximum slope at any point of the bottom profile is approximately 0.7^{o}. This indicates that a larger statistical sample than a few bottom profiles is required in order to find a relationship, if any, between the slope of a surface and its sediment thickness.

In Fig. 3, the slope at every point of the bottom data has been calculated and interpolated onto the sediment thickness map. The resulting dataset contains approximately $1.9x10^5$ data points. Visually, Fig. 3 indicates a clear relationship between the slope of the surface and its sediment thickness. And the average values of the bins only amplify this impression. However, when attempting to fit a function to the dataset, the picture is not as simple. An exponential decay seems to provide the best fit to the dataset. But if the fitting is done on the average bin values, it becomes very flat, as the same weight is given to the later bins, with less than 100 data points, as the earliest bins, with tens of thousands data points in each bin. Another method is to fit the exponential decay to the entire dataset. This obviously gives a very good fit at very shallow slopes, as this part has a high density of data points. However, the function seems to overfit to the earlier data and end up decaying towards zero sediment thickness extremely fast. By recognising that the fit on the entire dataset does in fact fit almost perfectly for shallow slopes, we can use this value to fix one parameter, the starting point (A), before fitting the rest of Eq. 1 to the average values of the bins. This results in a good fit to both the oversampled shallow slope cases and the undersampled steep slopes. The resulting exponential decay fit indicates a relationship between the slope of a surface and its sediment thickness that will tend towards zero sediment thickness at slopes of more than 10^o.

Employing the exponential fit found from the data in Fig. 3, the sediment thickness in the area can be estimated based solely on the slope of the bottom surface. This is implemented as one of the input parameters to the acoustic propagation model Lybin, where the modelled background level is compared to the measured background level from CEX02, right panel in Fig. 5. Here we see that by including the estimated sediment thickness from our results, the modelled background level performs worse at long ranges than the use of highly tuned range independent sediments [10]. However, it should be noted that there are many sources of error in the modelling, and the experiment was conducted in an area with highly varying oceanographic conditions. Furthermore, Lambert's law was used as a scattering kernel, where Lambert's coefficient was set to be constant along the profiles.

Although the range dependent model has an overall worse performance than the range independent model, individual samples, Fig. 4, indicate a higher correlation at certain ranges with the range dependent model. From our results it looks as if the sediments seen by the sonar on the upslopes towards the coast are softer than the bedrock properties used here. Furthermore, the models do not have enough degrees of freedom to account for the variations in the geoacoustic properties of the bottom. A similar model should be used to include a range dependent backscattering model.

6. CONCLUSION

By comparing seismic data and depth profiles, we have been able to find a relationship between the slope of the ocean floor and the thickness of the sediment present. This was done in an area in the Norwegian Trench with a relatively uniform sediment population consisting of mainly silt, sand and clay. The resulting relationship was then exploited in an attempt to improve upon previous acoustic modelling of backscatter in the area. The use of estimated sediment thickness in the models did not improve the modelled background level compared to previous range independent models. Whether this is due to the properties of the sediments in the upslopes towards the coast or other oceanographic properties is unknown. Although this is presenting a much quicker way of doing relatively accurate modelling of acoustic propagation based on bottom parameters. The method has only been tested in a very limited area with a relatively uniform sediment type and a very flat bottom.

Future work would have to expand the work done here by attempting to find relationships between the bottom slope and sediment thickness in other areas with a variation of sediments.

It would also be interesting to see whether different sediments have different relationships between slope and thickness. In Fig. 3 it is possible to imagine three distinct peaks of different sediment thicknesses at shallow slopes, and also possible to follow these peaks in what looks like three separate exponential decays. We hope to be able to follow up on this dataset and examine whether there is a link between these apparent peaks and their decays and certain positions in the map with particular bottom and/or sediment properties. Finally, we want to examine more closely the fact that soft range independent sediments provide a more accurate model of the background level towards the coast and upslopes than a range dependent model changing between the soft sediment type and bedrock.

REFERENCES

[1] **Eidem, E. J. & Landmark, K.**, Acoustic seabed classification using QTC IMPACT on single-beam echo sounder data from the Norwegian Channel, northern North Sea, *Continental Shelf Research*, 68, pp. 1-14, 2013.

[2] **Kara, E. M., Meghachou, M., & Aboubekr, N.**, Contribution of particles size ranges to sand friction, *Engineering, Technology & Applied Science Research*, 3, pp. 497-501, 2013.

[3] **Arvanitidis, C., Steiakakis, E., & Agioutantis, Z.**, Peak Friction Angle of Soils as a Function of Grain Size, *Geotechnical and Geological Engineering*, 37, pp. 1155-1167, 2019.

[4] **Jensen, F. B., Kuperman, W. A., Porter, M. B., & Schmidt, H.,** *Computational Ocean Acoustics*, Springer Science & Business Media, 2000.

[5] **Beerens, S. & Boek, W.**, A robust algorithm for LFAS target classification, *Undersea Defence Technology-UDT Europe*, 2007.

[6] **Schmidt, H.**, SAFARI: Seismo-Acoustic Fast Field Algorithm for Range-Independent Environments. User's Guide, 1988.

[7] **Schmidt, H.**, OASES Version 3.1. User Guide and Reference Manual. Department of Ocean Engineering Massachusetts Institute of Technology. February 20, 2004.

[8] **Kinsler, L. E., Frey, A. R., Coppens, A. B., & Sanders, J. V.**, *Fundamentals of Acoustics*, John Wiley \& Sons, Inc, pp. 560, 1999.

[9] **Ainslie, M. A.**, *Principles of sonar performance modelling*, Springer, pp. 800, 2010.

[10] **Søvik, A. A. & Hjelmervik, K. T.**, Comparison of measured and modelled reverberation and echo level in littoral waters, In *OCEANS 2017 - Aberdeen*, pp. 1-6, 2017.

[11] **Dombestein, E. & Wegger, K. E.**, Predicting sonar false alarm rate inflation using acoustic modeling and a high-resolution terrain model, FFI, 2014.