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TECHNICAL REPORT ON ASSESSMENT OF RUMBLE INVERSION RESULTS (DE18)

JENSERUD Trond (FFI,NO), KNUDSEN Tor (FFI,NO), DOMBESTEIN Elin M (FFI,NO), PLAISANT Alain (TUS,FR), CHALINDAR B (TUS,FR), AINSLIE, Michael (TNO,NL), ELLINGSEN Ingunn (KDA,NO)

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8) ABSTRACT

The main goal of project RUMBLE has been to enhance our capability to predict active sonar detection ranges in shallow water. The idea is to measure ‘through-the-sensor’ the seabed characteristics that affects long-range acoustic propagation in shallow water. The work has included the development of an inversion method for determining bottom parameters from reverberation received by a Low frequency Active Sonar (LFAS). Two sea trials have also been performed, in order to provide data for evaluating the performance of the method. The first sea trial took place in a relatively simple area in Vestfjorden, while for the second sea trial a more difficult area in the Norwegian Trench, west of Stavanger, was chosen.

The purpose of the present report is to make an assessment of the inversion results; to validate the results against ground truth, and to estimate the expected improvement of the RUMBLE method over predictions using standard databases.
It was found that reliable measurements could be made of the changes in backscattering strength, but not of sound speed or reflection loss. Ground truth collected during the trial, grab samples and 38 kHz echosounder, were found to be only weakly correlated with the LFAS measurements. This shows that near surface properties are of little use as an indicator of the effect of the seabed on LFAS.

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CONTENTS

TECHNICAL REPORT ON ASSESSMENT OF RUMBLE INVERSION RESULTS (DE18)

1 INTRODUCTION

Project RUMBLE aims at improving the capability to produce reliable predictions of active sonar ranges in shallow water, by measuring the relevant bottom properties by the ship's own Low Frequency Active Sonar (LFAS). There are several advantages in using own sonar to measure bottom properties: The bottom parameters are measured at the frequency and incidence angles of interest for the operational sonar and the method allows real time mapping of bottom characteristics during sonar operations.

The proposed method uses an inversion technique to determine bottom parameters relevant for bottom reverberation and reflection, from the reverberation returns of the ship's own sonar.

The work has included the development of the inversion method for estimating bottom properties from reverberation data, two sea trials to provide data for validating the concepts and evaluating the performance of the method, and the subsequent data analysis and operational assessment.

This report is deliverable DE18 of the RUMBLE project. The scope of the report is to make an assessment of the inversion results. More specifically, the bottom properties obtained by inversion have been validated against ground truth. The expected improvement of the RUMBLE method over predictions using standard databases and scattering index models has also been assessed.

The report is structured as follows: Sec. 2 sums up the main results of the sea trials, including both the acoustic data (reverberation) and the ground truth. Ground truth is acquired by different methods; both in situ measurements (grab samples) and HF acoustic measurements (echosounder). A best estimate of bottom properties is made, based on the different data sources including historical data. In Sec. 3 the performance of the inversion method is evaluated by comparing bottom properties obtained by acoustic inversion with bottom properties estimated from ground truth measurements. Sec. 4 contains a discussion of advantages and drawbacks of the method, and points out some areas of improvements. Finally, Sec. 5 contains the conclusions.

2 GLOBAL RESULTS

In this section the main results obtained during the project are summed up. First, the method for estimating bottom properties by an LFAS is briefly described. The properties and limitations of the method are discussed, based on synthetic reverberation data. Second, the sea trials are described briefly. The main results of the analysis of the reverberation data are presented as maps of inverted bottom parameters. Third, a best estimate of bottom parameters is synthesised from the different sources of ground truth data.

2.1 Acoustic inversion method

The performance of sonar in shallow water is very sensitive to seabed properties. The bottom parameters that determine the performance of LFAS systems are the scattering and reflection properties of the bottom at low grazing incidence and low frequency, and at fairly long distance from the sonar. If these parameters could be measured with the actual sonar, many of the problems and uncertainties associated with using ground truth recorded by other systems (at different frequencies, incidence angles and ranges) would be avoided. Such a measurement would also provide the potential for long-range coverage from a single platform.

Determining bottom properties from reverberation data is not an easy task: While traditional matched field methods use the forward propagating or coherent field, reverberation inversion uses the scattered, or incoherent, field. The properties of the reverberation field have implications on the inversion method, and will also affect the ability to extract bottom parameters from reverberation returns. Limitations arise among other things due to ambiguities.

Below, we describe the inversion method developed for the RUMBLE project, and discuss some of its properties, based on a study of synthetic reverberation data. We also include a brief description of the acoustic equipment used for the reverberation measurements, and the processing of the CAPTAS data prior to inversion.

2.1.1 Reverberation inversion

Traditional matched field inversion (MFI) relies on the spatial structure of the field to extract environment and field parameters. The approach requires coherence. Reverberation is a diffuse or incoherent field. Although reverberation contains information of the forward reflection properties of the seafloor, the scattering process causes the resulting field to be incoherent. In addition, the use of a horizontal array (only the broadside beam was used for the inversions) means there is no resolution of vertical angle. Hence, for reverberation inversion the forward problem is more challenging due to scattering, and the measurement contains less structure compared to MFI on forward propagation data. In practice, the inversion of reverberation data is usually carried out by matching beamformed data rather than individual hydrophones. It is therefore appropriate to refer to this as matched beam processing rather than matched field processing.

We will now consider the elements of matched beam reverberation inversion in some more detail.

The inverse problem

To perform inversion we need to define a set of *model parameters* **m**, which completely defines the system under consideration. These parameters may not all be directly measurable. To obtain information on model parameters we have to measure some *observable parameters or data* **d**. In our case model parameters may be geoacoustic properties of the bottom, such as sound speed and density, and the observable parameters are the reverberation field measured by the array. The observable parameters (data) may depend on the values of the model parameters to various extents. It is important that the data carry information about the model parameters we try to estimate. Although obvious, the experiment should be designed with this in mind.

To solve the *inverse problem* is to infer the values of the model parameters from measured values of the observable parameters. The components of an inversion scheme include i) a *forward model,* which predicts the values of the observable parameters given arbitrary values of the model parameters, ii) a *cost function* (often termed objective function) which measures the degree of agreement between observed and modelled data and iii) a *search algorithm* which maximizes the match between observed and modelled data by varying the model parameters.

Inversion starts with an initial guess of the model parameters and searches for the best model, i.e., the model that minimizes the objective function. However, due to i) experimental uncertainties (measurement errors and noise) and ii) modelling errors (mismatch) the predicted values cannot be identical to the observed values. It is therefore difficult to know whether the search algorithm has found the global minimum. Hence inversion may result in an *equivalent model* that is a poor representation of the real world, while nevertheless giving a good fit with data.

Parameterisation of the system

The choice of model parameters to describe the system is generally not unique. Here we consider the parameterisation of the bottom. The scattering and reflection properties of the ocean bottom can be described by a number of models, using a variety of parameters such as bottom type or porosity or sound speed, density and attenuation, etc. The scattering and reflection loss models range from simple empirical to complex physics based models, and the number of model parameters can be anything from one to more than ten. If the bottom properties are allowed to be range dependent, the number of model parameters may be extensive.

The complexity that is required for e.g. the bottom scattering model depends on the intended use of the results: For predictions with the same sonar system, a simple empirical model is probably adequate. If extrapolation to unmeasured frequencies and angles is important, a physics based model, including the most important scattering mechanisms should be used.
In practice, however, the number of parameters that can be determined by reverberation is rather limited. The important issue here is the sensitivity of the various parameters, i.e. to what degree a parameter influences the measurement.

The forward model

The forward model predicts reverberation power versus time after beamforming and matched filter processing. Two different reverberation models have been used during the project, REACT by TNO and TAMAR by TUS. The models contain local models for computing scattering and reflection loss at the sea surface and the seabed. Various local models have been applied. For bottom backscattering models with up to three parameters (variants of Lamberts rule) have been tested.

Objective function and search algorithm

The chosen cost function (objective function) measures deviations in the *shape* of observed and calculated reverberation curves, irrespective of the level. Hence a good solution can be found in the presence of systematic mismatch in level due to, for example, a calibration error on the measured data.

The Genetic Algorithm (GA) was selected as the search algorithm. GA is a global optimisation method that is well suited to find the optimum of a function of many variables.

Output parameters

Inverted parameters are the Lambert constant μ, and the sound speed c, attenuation α and density ρ of the sediment. Density is obtained from a known physical correlation with sound speed.

It was found that inverted values of sediment sound speed and attenuation are correlated with each other and highly variable. This is because different combinations of these parameters can give rise to approximately the same reflection loss curve. The bottom reflection loss (BRL) curve can be approximated (for small grazing angles) by

$$R(\theta) = \left(b / \pi\right)\theta$$

where θ is grazing angle and b is a reflection loss parameter (the slope of the reflection loss curve in dB/rad). The reflection loss parameter b is a combination of all three parameters c,α,ρ and is a more stable quantity. Therefore, inversion results are presented as maps of the scattering strength parameter μ and the reflection loss parameter b.

In a shallow water environment, the shape of the reverberation curve is largely determined by the slope of the reflection loss curve for the lower grazing angles.

Estimating parameters for reverberation models

An objective of the work is to provide geo-acoustic parameters that can be used by reverberation models to predict reverberation levels in the survey area. The Lambert parameter μ is already a suitable parameter, but the reflection loss parameter *b* is not. Due to high fluctuations the original inverted parameters c,α,ρ (from which *b* is computed) is not suitable. The following recipe is suggested for obtaining stable, physical parameters for reverberation models: (i) select a reasonable sediment sound speed, (ii) calculate density from known physical correlations with sound speed and (iii) calculate the attenuation consistent with the measured value of *b* [3] Sec. 6.7.

2.1.2 Properties of the method

Required signal-to-noise ratio

Inversion methods require sufficient signal-to-noise ratio to produce reliable results. In our case the signal is bottom reverberation, whereas surface and volume scattering are treated as noise. In a low signal-to-noise ratio environment, one may try to model surface and volume scattering. However, such an approach is hampered with large uncertainties.

There is also an inherent variance in the inversion method, such that a parameter can only be determined to within a certain tolerance.

Observability of bottom parameters

The inversion method tries to estimate the model parameters from measured values of some observable parameters. Some model parameters are sensitive, i.e. they have a significant influence on the measurement, and can be determined with good accuracy by inversion. Insensitive parameters are hard to determine, but their low sensitivity means they (usually) are of little importance. It may be advantageous to fix insensitive parameters during inversion. The sensitivity of a parameter is determined not only by the physics, but also by the cost function.

A study of the observability of bottom parameters has been carried out [6]. The study investigated how accurate bottom parameters (porosity) could be determined for several bottom types in the presence of ambient noise and surface reverberation, and for different oceanographic conditions. In general good results were achieved. The least favourable conditions were summer profiles combined with soft absorbing bottoms.

As an example of how model parameters affect the measurement consider a range independent medium where bottom scattering is governed by Lamberts rule, $\mu \cdot \sin^2(\theta)$, and bottom reflection loss has the form $b \cdot F(\theta)$. It can be shown [1] that (i) μ does not affect the shape of the BRL curve, only its level, (ii) the angle dependence of bottom scattering and reflection affects the shape of the reverberation curve, and (iii) the bottom reflection strength *b* affects the shape of the reverberation curve. A consequence of (i) and (ii) is that in a range independent medium bottom scattering and reflection can be separated.

The slope of the reverberation curve at short range is determined primarily by the angle dependence of the scattering strength. At longer ranges, where multiple bottom interaction becomes significant, the slope also depends on reflection loss.

Robustness to mismatch

The robustness of the method to mismatch in water depth, sonar depth, wind speed and sediment sound speed gradient has been studied in [1]. The main result is that the method is tolerant for small errors in the parameters considered. However, the conclusions depend to a certain extent on the actual bottom types and propagation conditions: As an example, the sensitivity to wind speed is less for a soft than for a hard bottom.

The sensitivity to mismatch in sound speed profile and bottom topography was considered in [6]. The study showed that reverberation is relatively insensitive to moderate variations in these parameters.

Sensitivity to parameter uncertainty has also been studied in [2] Sec. 6.5.2. The parameters chosen for the sensitivity study were sonar depth, water depth, sound speed profile and scattering law exponent.

Ambiguities

In all inversions there arise ambiguities whereby a measurement can be explained equally well by different combinations of parameters. Reverberation inversion is hampered with more ambiguities than conventional MFI. For the inversion method employed for the second sea trial ambiguities exist between:

- Bottom sound speed (critical angle) and bottom attenuation.
- Bottom scattering strength and bottom slope.
- Bottom scattering strength and bottom sound speed.
- Surface reverberation (wind speed dependent) and bottom scattering strength.
- Surface reflection loss (wind speed dependent) and bottom reflection loss.

As discussed above, c and α are correlated, such that a too high value of bottom sound speed is compensated by too high attenuation to produce approximately the correct reflection loss.

An upsloping bottom causes the reverberation level to increase. If the bottom is assumed to be flat, an overestimation of bottom scattering strength results.

The effects of surface scattering is twofold; first to cause increased reverberation level which may be misinterpreted as increased bottom scattering strength, and second to cause increased surface reflection loss which, if not accounted for, leads to overestimation of bottom reflection loss.

Range resolution and mapping of spatial variation

The ability of the method to resolve spatial variations in bottom parameters is limited by the ‘impulse response’ of a bottom facet. The impulse response of a bottom facet is a sequence of impulses corresponding to its eigenrays. The resolution is shown to be in the order of 50-200m, depending on the properties of the waveguide [6]. The mapping of horizontal variations of bottom properties is shown to be a difficult problem due to its non-linear nature [6].

2.1.3 Reverberation measurements: equipment and processing

The LFAS system

The LFAS system used for the reverberation measurements consisted of the SOCRATES towed source and the CAPTAS towed array. The acoustic section of the CAPTAS array has a length of 23 m and consists of 64 hydrophone triplets with a spacing of 36 cm. The hydrophones of each triplet lie on a circle with a radius of 50 mm. In active use the operating frequencies are between 1 and 2 kHz. Due to the triplet configuration the array is capable of port/starboard discrimination.

CAPTAS processing

Processing of reverberation data consisted of beamforming, matched filtering, and subsequent smoothing of the data to remove fluctuations, prior to inversion. Only data from the broadside beam has been considered for inversion. Triplet beamforming was applied, to obtain port/starboard discrimination. A (horizontal) beam resolution of 4^o was used.

For the temporal processing of hyperbolic frequency modulated (HFM) signals, regular matched filtering was applied. For processing of the continuous wave (CW) signals so-called “time series” processing was used. In this case the matched filter replica was approximated by a top-hat function in the frequency domain, acting as a bandpass filter with bandwidth of 320 Hz.

After beamforming and matched filtering some additional filtering was applied to remove fluctuations on different scales: First a running mean with window size 0.18 s to average over short scale random fluctuations (due to diffuse distribution of small scatterers), second a running median with window size 0.54 s to remove scattering from intermediate scale fluctuations (due to false targets) and third, a ping-average over 5 consecutive pings to remove ping-to-ping fluctuations.

2.2 Inversion of first sea trial data

2.2.1 Short description of the trial

The trial area

The first sea trial was conducted in Vestfjorden in May 2001 [8]. Two areas were selected for the measurements as shown in Figure 2.1. Both areas are squares of 15 by 15 nautical miles. Area A is located in the inner fjord and has a flat bottom with soft sediments. Area B is located at the entrance of the fjord and is expected to contain harder sediments as well as glacial scouring. The seabed of the areas comprises elongated ridges and depressions. These structures were formed by ice flowing towards southwest, along the main axis of Vestfjorden. The ridges and depressions consist of till material, whereas on top of the till surface a rather thin layer of layered sediments (marine/glaciomarine clays) may be found. In the northern part of area B the outer part of a large moraine ridge crossing Vestfjorden (the Tennholmen ridge) is found [12]. Figure 2.2 and Figure 2.3 show detailed topographic maps of the areas.

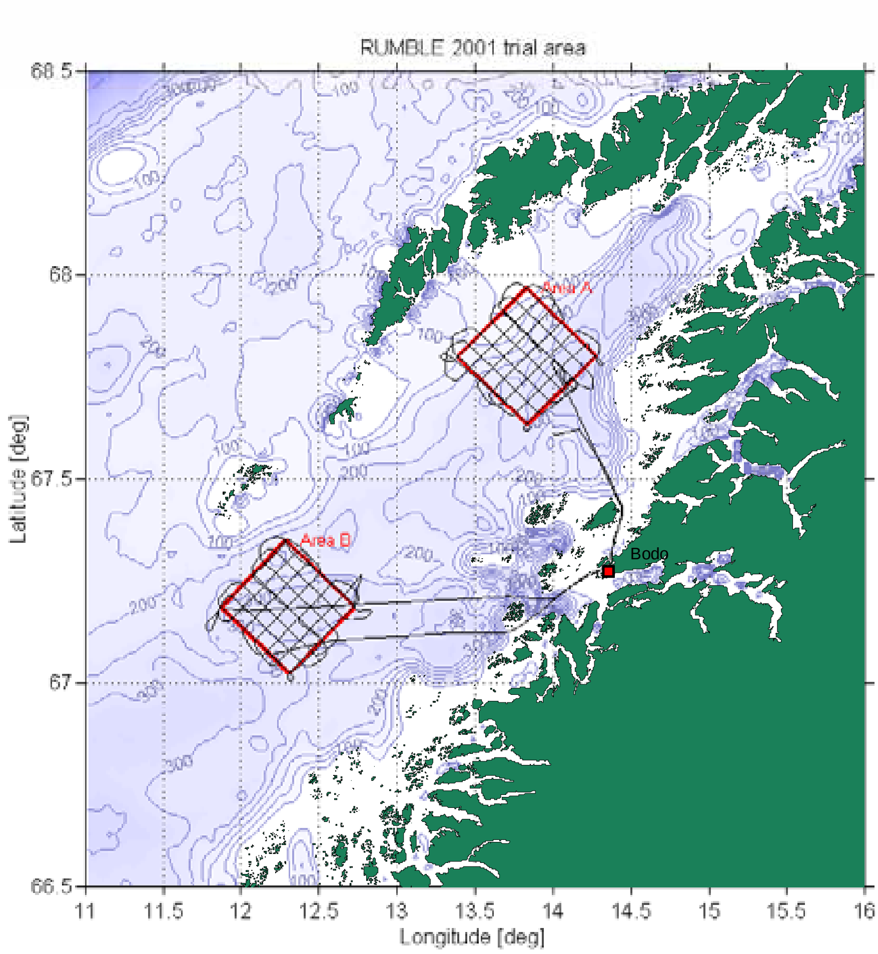

Figure 2.1 ([2] Fig. 2.1) The RUMBLE 2001 trial area. The two experiment areas, A and B, are indicated in red. The complete sailed track is marked by a black line.

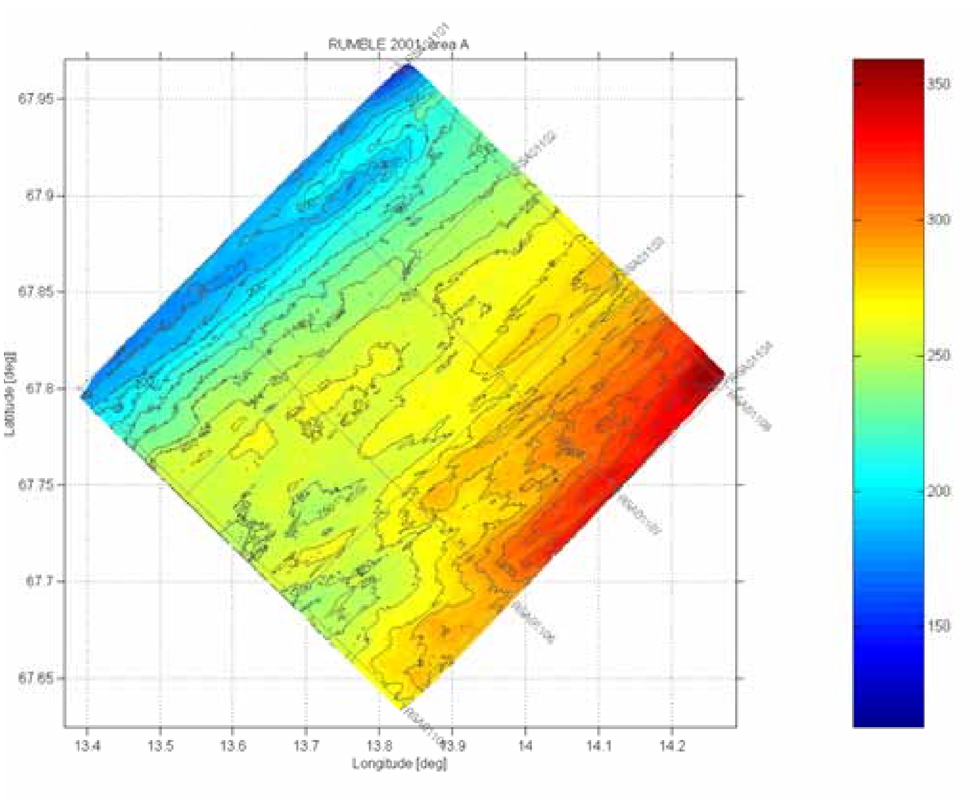

Figure 2.2 ([2] Fig.2.2) High resolution bathymetry for area A.

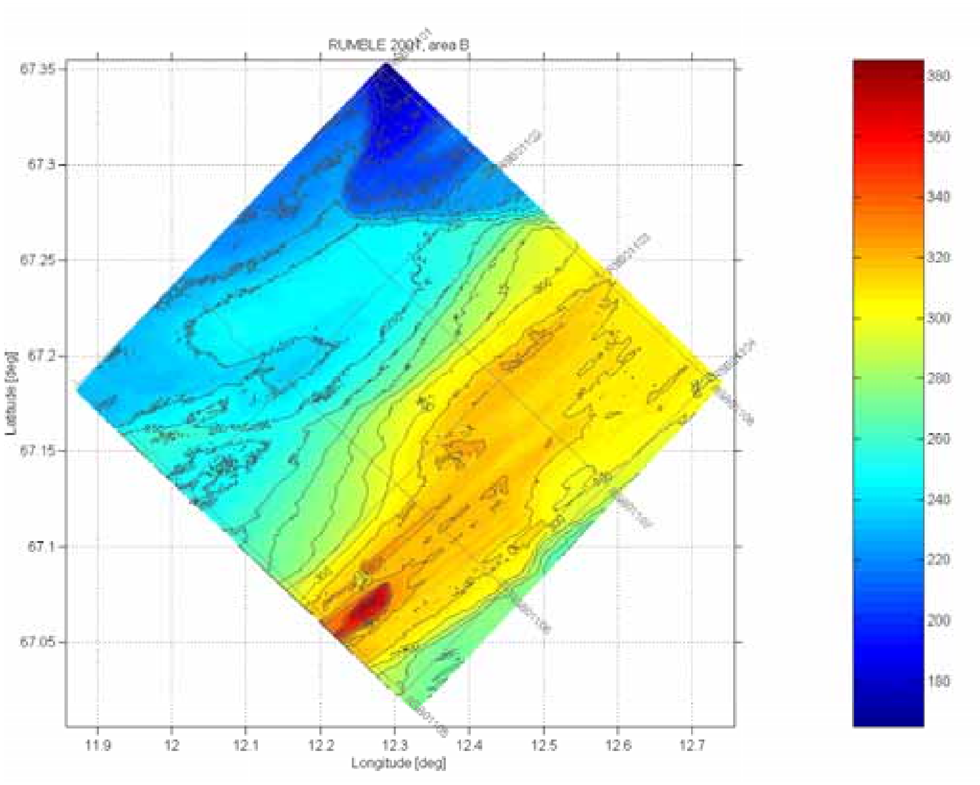

Figure 2.3 Fig 2.2.1-3. ([2] Fig.2.3) High resolution bathymetry for area B.

Reverberation measurements

The reverberation measurements were made with the SOCRATES sound source and the CAPTAS towed triplet array. Both source and receiver were placed at the same depth (50 m) for area A, and different depths for area B. Horizontal separation between source and array (acoustic module) was 150 m.

The transmitted signal was a burst composed of a short CW pulse of duration 10 ms at centre frequency 1.5 kHz followed 5 s later by a Hyperbolic FM pulse from 1 to 2 kHz of duration 5 s. The repetition rate was 60 s. The source level was 205.5 dB re 1 μPa @ 1m.

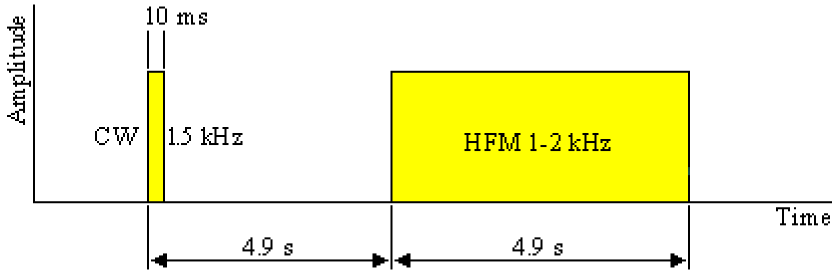

Figure 2.4 ([2] Fig. 2.4) Transmitted signal by SOCRATES.

Ground truth measurements

Ground truth collected during the trial consisted of grab samples [13], echo sounder data (analysed with QTC software packages) and sub-bottom profiling (using TOPAS parametric sonar). Supporting oceanographic, bathymetric and meteorological data were recorded during the trial.

Run tracks

The experiment areas were covered at two different courses: along the fjord axis (heading 44° or 224°) and across the fjord axis (heading 134° or 314°). The reason for running perpendicular courses, is that anisotropy is expected in the bottom properties. Figure 2.5 and Figure 2.6 show the tracks for the reverberation measurements (in red) and TOPAS measurements (in blue) for both experiment areas. In each area reverberation measurements have been carried out along four legs along the fjord axis (beam across fjord) and four legs perpendicular to the fjord axis (beam along fjord axis).

Seven grab samples were taken in area A, along leg 7. In area B 10 grab samples were taken, evenly distributed over the area. CTD casts were performed at the same positions as the grab samples. As significant oceanographic variability was expected in the area, 23 XBTs were launched during SOCRATES runs in area A, and 21 in area B.

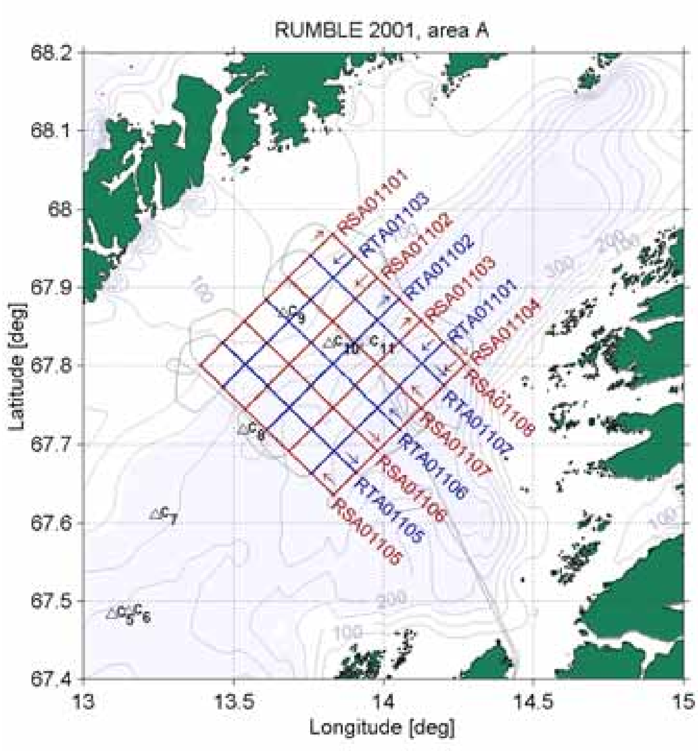

Figure 2.5 *([2] Fig. 2.6) Run tracks for area A. SOCARATES runs are marked in red and TOPAS runs are marked in blue. The arrows show the direction in which the tracks were sailed.*

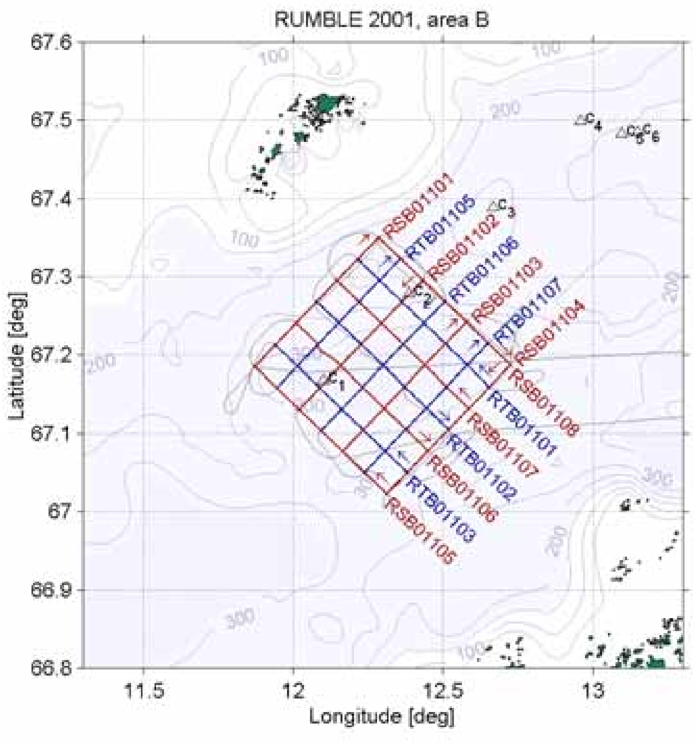

Figure 2.6 *([2] Fig. 2.7) Run tracks for area B. SOCARATES runs are marked in red and TOPAS runs are marked in blue. The arrows show the direction in which the tracks were sailed.*

2.2.2 Problems encountered

Interference

During the reverberation measurements, several other acoustic systems were also in use in order to collect background data that could be used for investigating the quality of the inversion method. It is very important that these parallel acoustic measurements do not in any way interfere with the CAPTAS/SOCRATES measurements. Several runs were therefore done with different equipment switched on or off. On board monitoring of reverberation in the broadside beam, with no left right ambiguity processing, seemed to confirm that there was no interference from the echosounder and the high power TOPAS parametric sonar.

Unfortunately it was later revealed that TOPAS in some way interfered with the port/starboard ambiguity processing. Strangely enough the interference could not be seen when standard beamforming, without port/starboard ambiguity processing, was used in the lab. This indicates, at least, that the data had not suffered degradation during storage on digital tape.

In Figure 2.7 one can see the interference from TOPAS transmission. Several methods were tried to reduce the interference, but it was impossible to reduce it to a level where it would not interfere with the inversion.

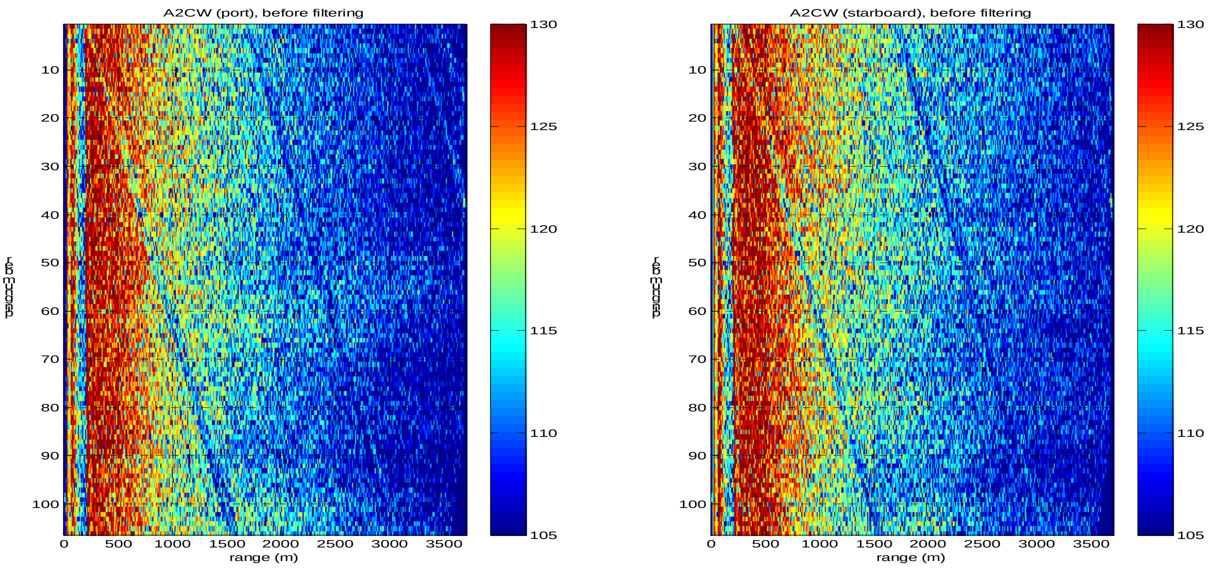

Figure 2.7 ([2] Fig. 6.2) Processed CW data for leg A2 (total reverberation) for port beam (left) and starboard beam (right).

It is very surprising that TOPAS interfered with the CAPTAS sonar. No interference was observed on the towed array beams that were not processed to solve the port/starboard ambiguity problem. It was only after this processing that the problem turned up. The other surprising fact is that primary frequencies of the sonar are between 18 kHz and 22 kHz. The parametric generated difference frequency is within the CAPTAS frequency band, but this signal is between 30- 40 dB lower in level than the primary frequencies. In addition it is only present in a narrow beam with beamwidth of about 5 degrees that points straight down. The interference has about the same level in all beams, indicating that the cause may not be acoustic.

SNR and usable range

Another important observation was made. Each transmission consisted of two very different signals as shown in Figure 2.4. The first signal was a short CW intended for short-range reverberation measurements, while the second signal was a long Hyperbolic FM sweep transmitted after the reverberation from the CW had disappeared. When the CW results were used for inversion several problems surfaced:

- At very short ranges (less than 1 km) the reverberation is bistatic, as there is a considerable displacement between the source and the receiver array.
- It was not possible to consider reverberation from the CW pulse for longer ranges that 3.5 km due to the onset of the HFM pulse
- The reverberation died out so fast that there were only a few km of reverberation that could be used for monostatic inversion. None of the available acoustic models were capable of handling range dependent bistatic modelling.

Reverberation from the second transmitted signal, the 5 s HFM sweep, can only be measured after the transmission have finished and the fathometer returns have died out, approximately 6-7 seconds from the start of the transmission. This is equivalent to ranges of about 4.5 to 5.2 km. As the ranges get longer it will be more difficult to separate bottom, surface and volume reverberation. The emphasis should therefore be to invert data from reasonably short ranges first.

At this time the results from the second sea trial became available. In this experiment a third signal for measuring reverberation in the range interval between the short CW and the HFM signal had been introduced. It was therefore decided put all remaining effort into analysing reverberation from this new signal

2.2.3 Lessons learned

From the first sea trial and subsequent analysis the following observations may be made:

- Inversion procedures are looking for small deviations in the backscattered signal. Interference from other acoustic sources may give erroneous results.
- The transmit and the receive arrays are at different distances from the towing ship. In an operational low frequency active sonar the difference may be 500m. At short ranges a bistatic acoustic model is needed for inversion.
- The 10 ms long CW give too low reverberation level at ranges where monostatic acoustic models can be used for finding reverberation parameters.
- For the 10 ms CW pulse, the range window that can be exploited for reverberation inversion is 1 to 3.5 km. The upper limit is due to the onset of the HFM pulse. Shorter ranges than 1 km would require a bistatic model. Monostatic geometry was assumed for this work.

2.3 Inversion of second sea trial data

2.3.1 Short description of the trial

The trial area

The second sea trial was carried out at location (59.2° N, 4.5° E) in the Norwegian trench in September-October 2002 [10]. The measurement area is a square of dimensions 20 by 20 nautical miles, as shown in Figure 2.8. The bottom in the area is relatively flat, with water depth in the range from 250 to 285 m for most of the area. The shallowest areas are found in the eastern part where a few seamounts rise to some 180 m. The measurement area contains several bottom types: soft clay, stiff clay and exposed rock. Sediment thickness also varies considerably over the area. Iceberg (Glacial) scouring is found in the area with general orientation in the N-S direction. The area has a complex oceanography due to the influence of the Norwegian Coastal Current.

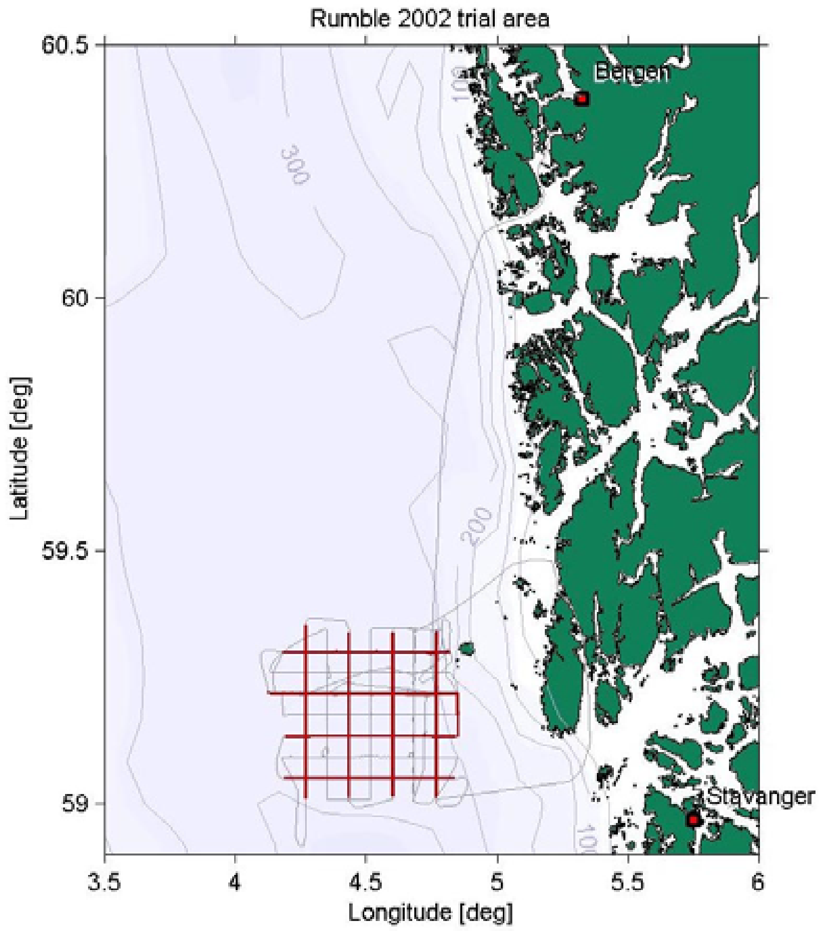

Figure 2.8 ([3] Fig. 2-1) The RUMBLE 2002 trial area. The complete sailed track is marked by a grey line. LFAS reverberation measurements were carried out along the red lines.

Reverberation measurements

The reverberation measurements were made with the SOCRATES sound source and the CAPTAS towed triplet array. The transmitted signal was composed of three pulses, as shown in Figure 2.9: Two short CW pulses centred at 1.5 kHz and of duration 10 ms and 100 ms respectively, and a Hyperbolic FM pulse from 1 to 2 kHz of duration 6.4 s. The pulses were transmitted in sequence with sufficient delay to allow reverberation from previous pulse to decay. The overall repetition rate was 90 s. The source level was 205.5 dB re 1 μPa @ 1m. The tow configuration was optimised for bottom interaction, with the restriction that cable scope is limited by water depth. The source was towed at a depth of 50-60 m, while the receiving array depth varied between 65-75 m.

Ground truth and environmental data

Ground truth collected during the trial consisted of grab samples, echo sounder data and sub-bottom profiling, and is described in Sec. 2.4.

Supporting oceanographic, bathymetric and meteorological data were recorded during the trial. Figure 2.10 and Figure 2.11 show sound speed profiles (SSP) collected during the trial. The profiles indicate that there are two water masses (a frontal region) within the survey area: The profiles within the eastern part of the area are smooth, showing a small surface duct in the top 20 m and a thermocline with a large bottom channel below 50 m. The profiles in the western part are highly fluctuating below 50 m, and also show much higher spatial variability and generally higher temperatures.

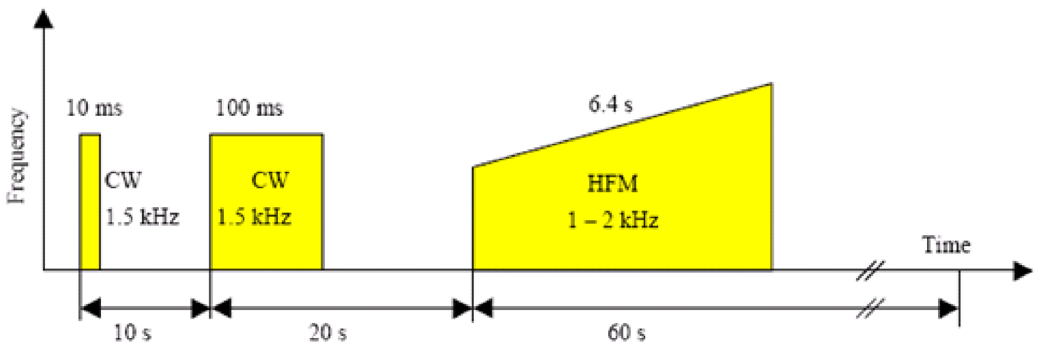

Figure 2.9 ([3] Fig 2-3) Signals transmitted by SOCRATES. Overall repetition rate is 90 s.

Run tracks

Since horizontal anisotropy may sometimes occur for bottom scattering, the same scattering element must be observed at various angles. It was therefore decided to cover the area at two different ship courses: perpendicular to bathymetry contours (heading 90° or 270°) and parallel to bathymetry contours (0° or 180°). Figure 2.12 shows sailed tracks for the reverberation measurements. We were also able to rerun three legs with different (higher) wind speed. These data were recorded in order to test the reproducibility of results under different weather conditions.

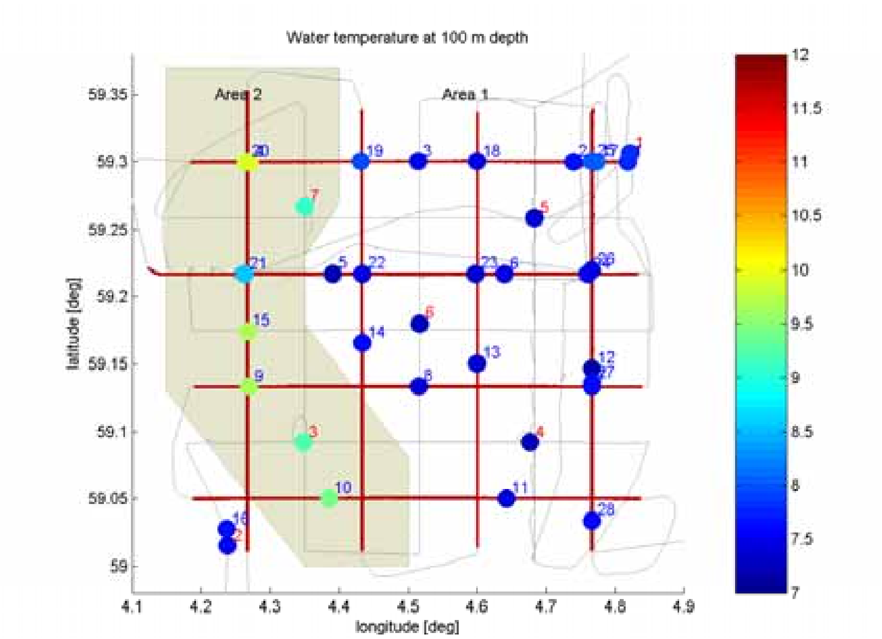

Figure 2.10 Fig. 2.3.1-3a. ([3] Fig. 4-7). Sound speed profiles collected during the trial. The figure shows the locations of the CTD and XBT casts, and the temperature at 100 m depth. Two areas with different water masses are indicated in the figure.

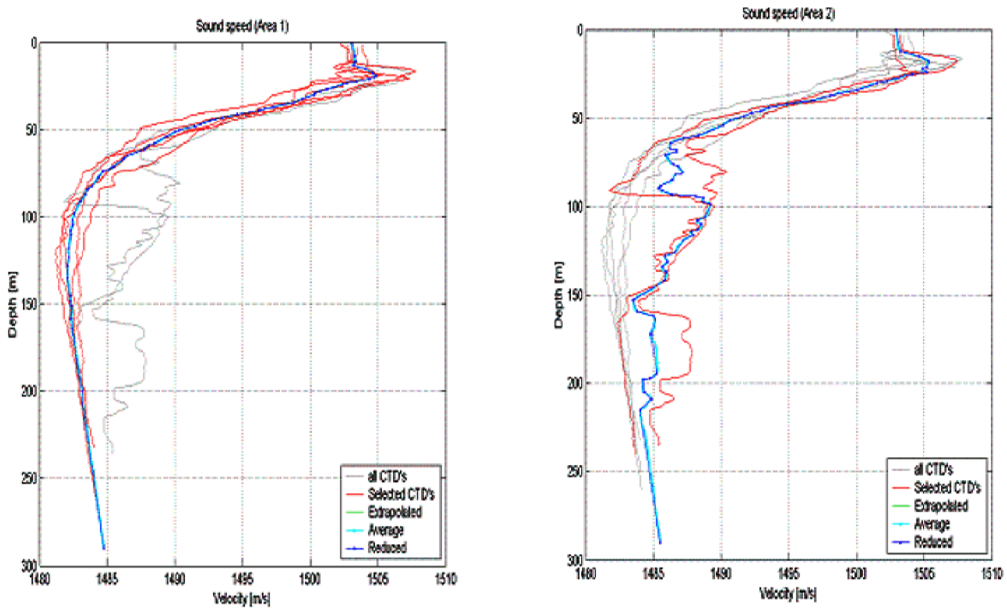

Figure 2.11 ([3] Fig. 4-6). Sound speed profiles collected during the trial. Left panel shows all profiles in area 1 (red), the average profile in area 1 (blue) and the profiles in area 2 (grey). In the right panel the profiles in area 2 is shown in red, and the average profile in area 2 is shown in blue.

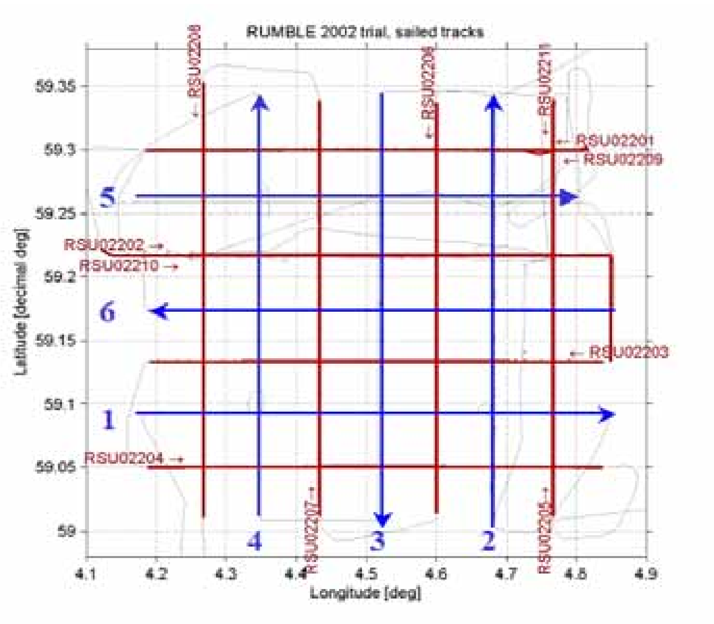

Figure 2.12 ([3] Fig. 2-4) Sailed tracks for reverberation measurements. Red lines are CAPTAS tracks. The last two digits in the experiment name denote leg number. The blue lines are TOPAS tracks. The tracks are annotated with leg no. The sailed direction is also indicated.

2.3.2 Data used for inversion

Data used for inversion are the broadside beam reverberation from the long (100 ms) CW pulse, for all legs. Four legs (1,2,3,4) run in east-west direction, with the broadside beam along the glacial scouring, and four legs (5,6,7,8) run in north-south direction, with the broadside beam across the glacial scouring. Run 9,10 and 11 are re-runs under higher sea state of legs 1,2, and 5 respectively.

The transmitted signal consisted of three pulses in sequence: a 10 ms CW, a 100 ms CW and a 6.4 s HFM pulse. The short CW pulse has low energy and is useful only for analysing short (bistatic) geometries. The medium energy, medium range 100 ms CW pulse and high energy, long-range HFM pulse have available time windows for reverberation analysis of 1-20 s (15 km) and 7-90 s respectively. For the last pulse range dependent bathymetry and SSP are needed. It was decided to concentrate effort on the 100 ms CW pulse for the inversions because this pulse is less sensitive to sound speed profile and bathymetry.

2.3.3 Inversion method

The inversion method is basically as described above in Sec. 2.1: Measured reverberation curves are compared to synthetic reverberation curves computed for a range of bottom parameters. The model parameters that give the best match with data are selected as the true bottom parameters. We did not use any information from the echosounder to carry out the LFAS inversions.

Pre-processing:
Triplet beamformed data is filtered prior to inversion, using the procedure of Sec. 2.3.1.

Forward model:
The forward model is the TAMAR reverberation model [5]. TAMAR is a fast ray based model that handles range-dependent bathymetry by a perturbation technique. The model assumes range independent sound speed profiles. Bottom backscattering is modelled by Lamberts rule,
$\sigma = \mu \sin^2 \theta$,
where μ is the Lambert constant and θ is the grazing angle. Bottom reflection loss is modelled by the Rayleigh reflection coefficient,

$$V = \frac{m \sin\theta - \sqrt{n^2 - \cos^2\theta}}{m \sin\theta + \sqrt{n^2 - \cos^2\theta}},$$

where $m = \rho/\rho_w$, $n = c_w/c = k/k_w$. Here ρ, ρ_w is density for sediment and water respectively, c is sound velocity, k is wavenumber, and θ is the grazing angle. Loss in the sediment is modelled by a complex wavenumber, $k = |k|(1+\delta)$, where δ is the loss tangent. Loss tangent is related to attenuation by $\alpha[dB/\lambda] = 54.58\delta$.

Environmental inputs:
A range independent environment is assumed. The sound speed profile is an average profile for the area, and the water depth is taken to be the depth at the source (for each ping). For the inversions a flat sea surface (no wind) is assumed.

Objective function:
The objective function is somewhat different from that described above: The value of μ is determined from reverberation data in the window 1.3-2.2s, where the direct ray dominates; hence reverberation is independent of bottom reflection loss. Using this value of μ, the other sediment parameters (c, ρ and α) are determined by matching data over the time range 1.3-7.0s, with the exception of a caustic region for times 2.2-3.6s. Density is not estimated independently, but is determined by the empirical relation ([1] Eq 4.5.4).
Results are presented in the form of scattering strength μ and the reflection loss parameter b instead of c and α due to the inability of the inversion method to resolve these parameters, as discussed in Sec. 2.1.1.

The inversion method has been tested on synthetic reverberation data [3] Sec 5. The main conclusions were that

- The scattering strength can be measured to an accuracy of ±2-3 dB.
- The inversion for reflection loss is hampered by uncertainty in the forward modelling.

2.3.4 Main results from inversion

The main results of the analysis are maps of inverted parameters for scattering strength μ and reflection loss parameter *b*. Since *b* is singular (infinite) when the sound speed in the sediment is equal to that in water, results are presented as π/b. In the maps shown below, the results from north-south (NS) and east-west (EW) legs are merged together in one map.

Scattering strength

Figure 2.13 shows averaged final results from all legs of μ and π/b. Significant changes in scattering strength, up to 15 dB, are found across the survey area. For scattering strength μ there are four clearly identifiable regions:

- An area of low μ to the south-east (south of leg 5)
- An area of low μ to the north north-east (north of leg 6)
- An area of high μ to the south-west
- An area of very high μ near the centre of the eastern-most strip (leg 5), close to the locations of the seamounts.

Scattering strength is azimuthally anisotropic.

Reflection loss

The patterns of reflection loss values *b* are less obvious. Going from west to east there is a general trend of increasing π/b values (reduced reflection loss) consistent with the increasing grain size in this direction. There are also patches to the east in the grid with very low reflection loss (black) and very high scattering strength (white). The patches correspond to places where the array passes very close to a cluster of seamounts.

Sound speed and attenuation

Inverted values for sediment sound speed and attenuation are only available for leg 7. Leg 7 has uniform water depth and bottom type. The average value for *c* is about 1700±50 m/s, and for α about 1.8 ±0.5 dB/λ. There is a large spread in the values of *c* and α. The values of *c* and α are also strongly correlated.

Azimuthal anisotropy

In the western part of the survey area the north-south legs resulted in significantly higher reverberation (about 4 dB), and correspondingly larger values of μ, than the east-west legs over the same seabed. A possible cause of this azimuthal anisotropy of scattering strength is the presence of iceberg scouring marks with a general alignment in north-south direction.

Reproducibility of results

Measurements of scattering strength are reproducible for repeated legs over the same area. The repeated measurements were carried out in higher wind conditions. These results show that the effects of the wind (surface scattering and reverberation) are modelled correctly in the inversion. The sensitivity to wind speed depends on the amount of interaction with the sea surface.

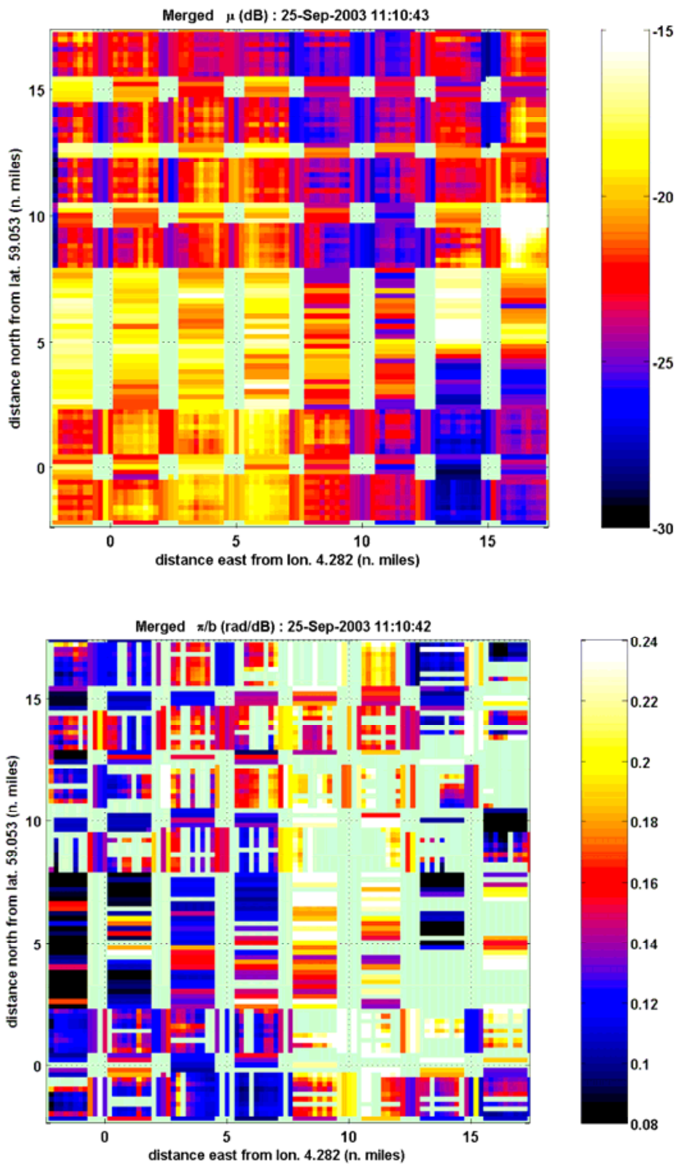

Figure 2.13 *Maps of inversion results. Top graph:* μ *versus latitude and longitude. Bottom graph* π/b *versus latitude and longitude.*

2.3.5 Problems encountered

Calibration

There have been some problems in determining the correct calibration factor for the CAPTAS processor. The calibration factor applied is selected to produce physically reasonable values for the scattering strength.

Ambiguities

The inversion method is not able to resolve sound velocity and attenuation in the sediment. The reason is that these parameters are highly correlated, such that too high values of c is compensated by too high values of α to produce the approximately correct reflection loss. It may therefore be necessary to determine c and α from other measurements, such as echosounder or short range measurements. Another way of resolving such ambiguities is by exploiting multiple looks at the same patch of the seabed, from different distances.

Reverberation model

The reverberation model has been identified as a source of uncertainty: As a consequence, one should ideally use the same reverberation model for predictions as used for the inversion.

2.3.6 Swath range obtained

The range window exploited for reverberation inversions, using the100 ms CW pulse, was 1 to 3.7 km. At shorter ranges than 1 km a bistatic geometry would be required. At longer ranges than 3.7 km the SNR was typically less than 5 dB, so that the background noise could not be ignored. The swath range within which successful inversion for bottom parameters can be obtained depends on a number of factors: bottom type, sea state and ambient noise level as well as source and receiver depth.

The RUMBLE analysis has concentrated on the short-range data. One reason is that we would like to demonstrate that reliable results could be obtained at shorter ranges with fairly range independent parameters before moving to the more difficult long-range range-dependent case. Another reason is a lack of long-range SSP data, which would make it difficult to separate temporal variations from spatial ones, and hence cause problems with the interpretation of the results.

2.4 Ground truth measurements (for second sea trial)

Ground truth collected during second sea trial consisted of grab samples, echo sounder data, sub-bottom profiling using TOPAS, and high-resolution bathymetry.

The grab samples provide the only true ground truth of bottom type. Grab sampling is very time consuming, and necessarily results in sparse sampling. Grab samples were collected along one vertical and one horizontal leg.

The echosounder provides an alternative, indirect measurement of bottom properties, and is used to extend the grab measurements to cover the whole of the ship track.

The TOPAS sonar provides thickness of the sediment layers. Such information is valuable in the interpretation of inversion results since layering and hidden roughness may influence CAPTAS results as well as echosounder pulse shapes. TOPAS data were collected along three vertical and three horizontal legs.

Information about bathymetry is also valuable in interpreting results. First, there is often some correlation between sediment types and terrain: In general flat parts and depressions contain soft sediments while the sloping parts contain harder sediments. Second, bottom slope also influences backscattering strength. High-resolution bathymetry was collected in a part of the area, centred on the grab sampling legs. Echosounder data was used to obtain depth information along the whole of the ship track.

2.4.1 Historical data

Geological description of trial area

The geology of the RUMBLE survey area is relatively well known due to a pipeline-route survey that was conducted by Statoil in the area. Hovland [16] has investigated a small area 12 km south-south-west of Utsira containing a depression parallel to the coast. Figure 2.14 shows the area studied by Hovland and the RUMBLE survey area. The topography and sediment distribution within the study area is given in Figure 2.15. The area has a generally westward-sloping seabed. In the eastern part of the area two hills are rising some 30 m above the general seabed. The hills consist of exposed crystalline bedrock with a thin cover of sand and silt in places. To the west of the two hills the crystalline bedrock dips under a layer of stiff clay. The stiff clay has been furrowed by floating icebergs. The iceberg gouges run in a north-south direction and are typically 2-3 m deep and 50-150m wide. At depths below 250-260 m soft, silty, layered clays overlay the stiff clay. The underlying stiff clay may also here have been gouged by icebergs prior to sedimentation of the top unit. A depression running parallel to the coast, possibly formed by escaping gas, is indicated in the figure.

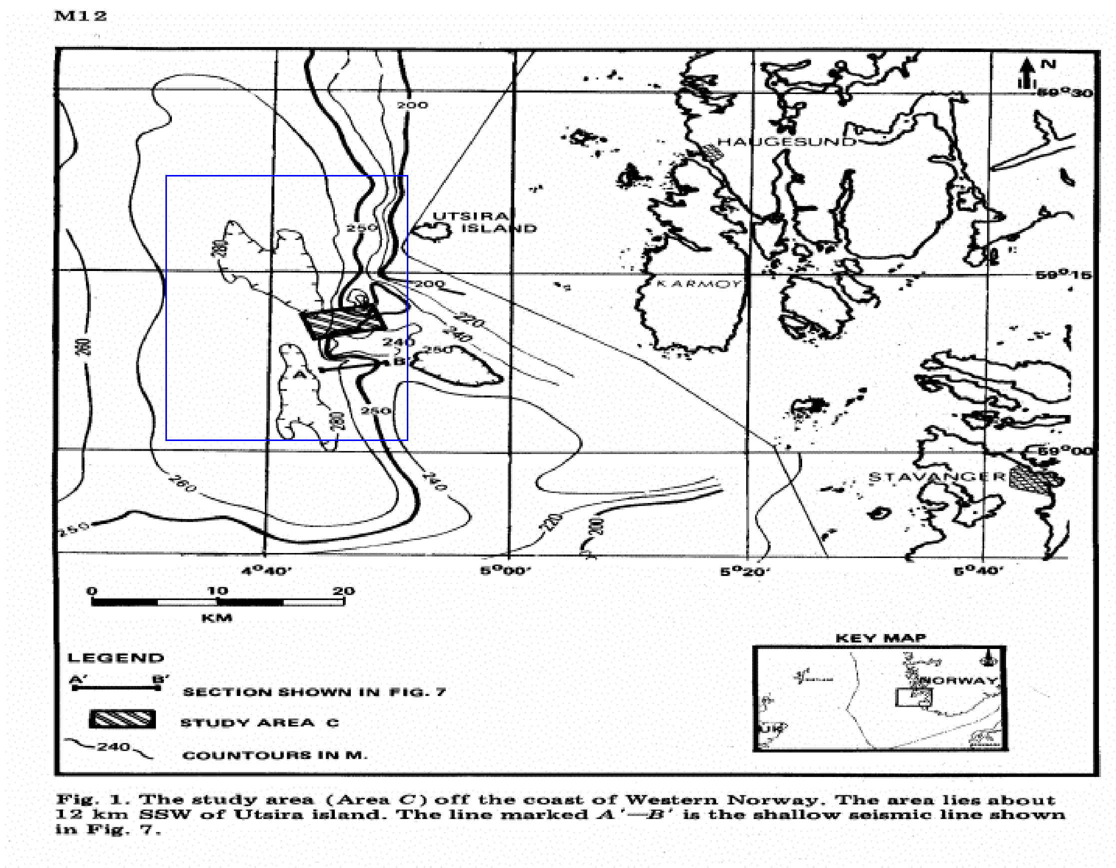

Figure 2.14 ([16] Fig.1.) RUMBLE survey area (blue) and Hovland study area off the coast of Western Norway.

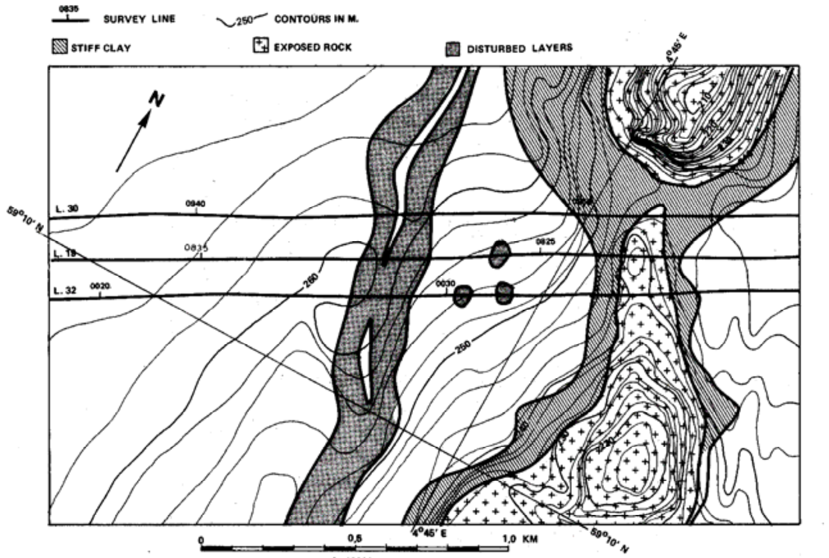

Fig. 2. Area C showing topography, the coast-parallel depression, survey lines and sediment distribution.

Figure 2.15 ([16] fig.2.) Topography, sediment distributions and survey lines of Hovland study area. The coast-parallel depression is indicated (It is located along the disturbed layer).

2.4.2 Grab samples

We first include some general information on the properties of surface sediments, and then move on to the analysis of the grab samples collected during the second sea trial.

Some properties of surface sediments

Sediments can be classified by their mean grain size, M_Z. The mean grain size is defined as the mean of the 16th, 50th and 84th percentiles of the grain size distribution

$$M_Z = \frac{\varphi_{16} + \varphi_{50} + \varphi_{84}}{3},$$

where the φ values are defined by minus log_2 of the grain size in millimetres, and φ_{16}, φ_{50} and φ_{84} denotes the grain size for which 16%, 50% and 84% respectively of the sample (by weight) has a smaller grain size. Table 2.1 shows the definition of sediment classes used in the present work. A compilation of sediment properties ([3] Sec. 2.1) as a function of mean grain size is given in Figure 2.16. The figure shows expected values of sound speed ratio, density ratio, attenuation and reflection loss parameter π/b. Also shown in the figure are the standard deviations of the parameter estimates.

Analysis of grab samples

Bottom grabs were collected along one of the horizontal and one of the vertical legs of the RUMBLE grid, as shown in Figure 2.17. The grab samples have been analysed (by Norwegian Geological Survey) for grain size [14].

Sediment type	Mean grain size (M_Z)
Fine sand	2 - 3
Very fine sand	3 - 4
Coarse silt	4 - 5
Medium silt	5 - 6
Fine silt	6 - 7
Very fine silt	7 - 8
Coarse clay	8 - 9

Table 2.1 Definition of sediment classes [18].

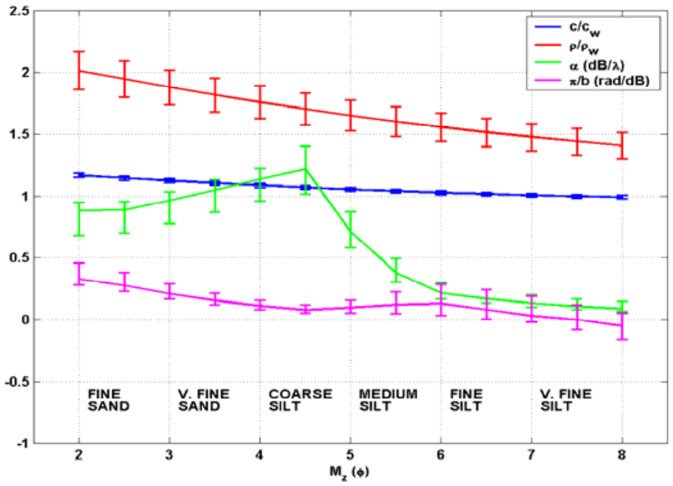

Figure 2.16 ([3] Fig. 6-1. Expected values and uncertainty of c/c_w, ρ/ρ_w, α/α_w *and* π/b, *as a function of mean grain size.*

Figure 2.17 shows the location of grab samples. The marker colours in the figure correspond to mean grain sizes M_Z. The corresponding sediment classes can be found from Table 2.1. Surface sediment types in the area ranges from very fine silt (M_Z =7.6) in the western and south-eastern part, to fine sand (M_Z =3) in the eastern part. In general, the hardest sediments are found in the shallowest parts and steepest slopes. The geoacoustic properties of the sediment as a function of mean grain size are given in Figure 2.16.

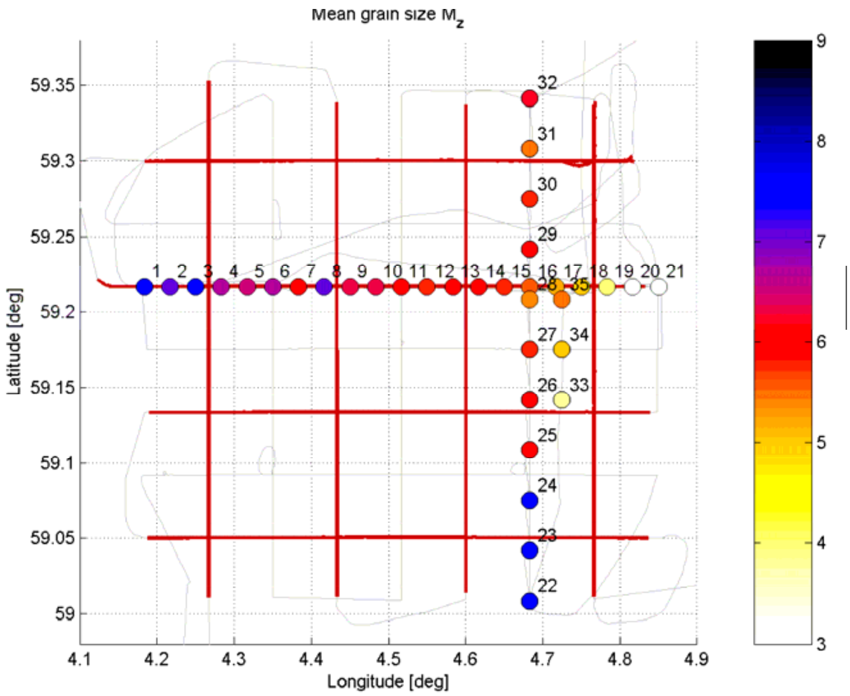

Figure 2.17 ([3] Fig. 4-11) Positions of grab samples. Markers correspond to mean grain sizes M_Z.

2.4.3 Echo sounder data

The signal (echo envelopes) from the ships 38 kHz echosounder was recorded continuously during the survey. The echo envelopes were subject to various analyses: i) QTC analyses for sediment classification, ii) extraction of echo features such as time spread and energy, iii) estimation of sediment properties such as sound velocity and density and iv) extraction of water depth from the return time of the echosounder signals.

QTC processing

QTC is a commercially available seafloor classification device. QTC works by extracting a number of features for each echo, followed by a cluster analysis to find groups of echoes corresponding to different bottom types. The output of QTC analysis is not specific bottom types; the analysis just discriminates between bottoms with different properties. A calibration against ground truth, such as grab samples, is necessary to assign specific bottom types to the different groups found by the QTC analysis.

Figure 2.18 shows results from QTC classification. The results indicate that four different surface sediment types are found within the area.

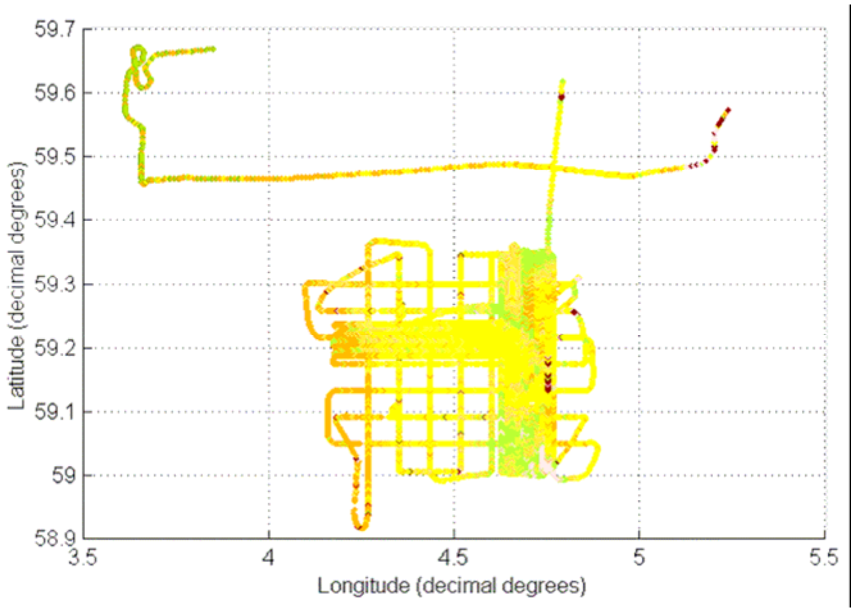

Figure 2.18 ([3] Fig. 4-14) QTC classification results for the RUMBLE grid. Different colours correspond to different bottom types.

Feature extraction

Several features were calculated from the echo envelopes: Echo energy, echo time spread and skewness (a measure of echo symmetry). Although the reason for using these particular statistical moments was nothing more than finding discriminating features, some of these quantities can be related to specific bottom properties: Echo energy (when corrected for propagation loss) is a measure of bottom reflection coefficient (uncalibrated). Echo time spread (when corrected for propagation loss and sonar footprint size) is a measure of bottom roughness.

A classification based on clustering in the energy-time spread domain is demonstrated below. In addition to the features mentioned above, a simple inspection of the shape of the echo envelopes may also reveal important information about the sediments.

Sediment classification by energy and timespread of echosounder pulse

A qualitative discrimination between different sediment types can be made from features extracted from echosounder returns. The top panel of Figure 2.19 shows that some degree of clustering occurs when the echo timespread and energy are plotted against each other. A colour coding is applied to the clusters, as shown in the middle panel: Red: echoes with high energy and low timespread, indicating a hard, smooth bottom. Purple: echoes with high energy and high timespread, indicating a hard, rough bottom. Yellow: medium energy, low timespread, indicating a medium soft, smooth bottom. Brown: low energy, high timespread, indicating a soft, layered bottom.

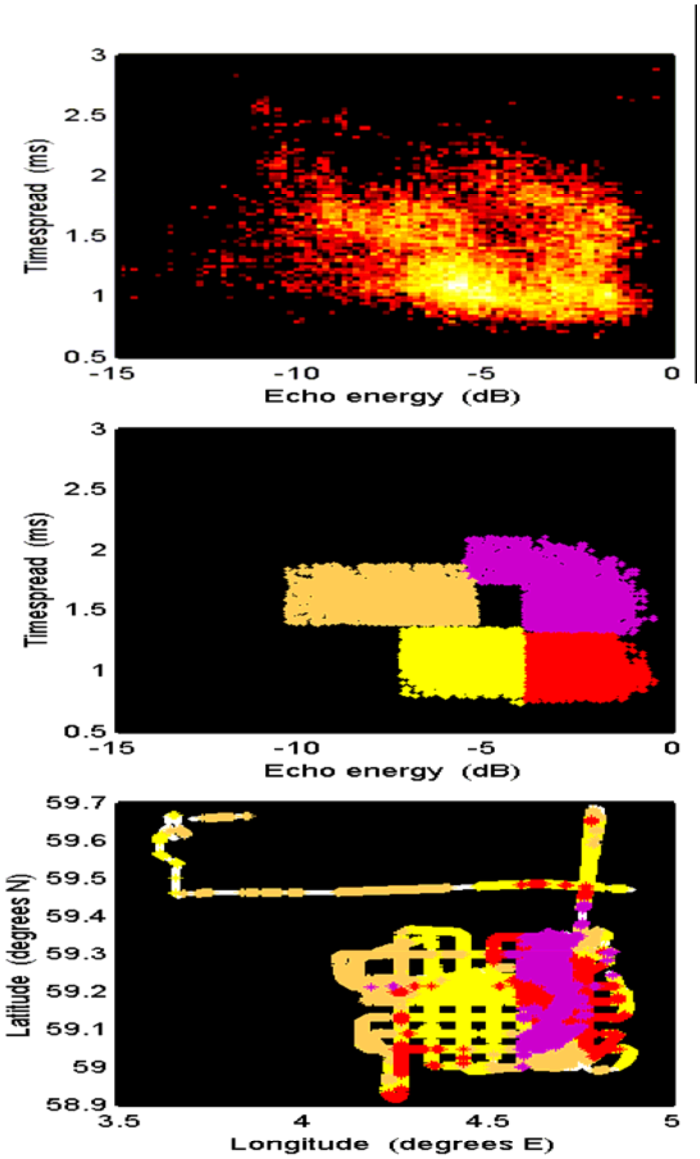

Figure 2.19 ([3] fig 4-18, 4-19). Classification on basis of clustering in the energy-timespread domain. Top graph shows echo energy and timespread plotted against one another. The middle graph shows the colour coding applied to the clusters observed in the top graph, and the lower graph shows the resulting classification for the grid.

The lower panel of the figure shows classification based on the clustering in the energy-timespread space. Clear differences are seen between different parts of the grid. The boundary between yellow and purple is very distinct and aligned parallel to the coastline, indicating a transition from softer to harder sediments as we move towards the coast.

There is some consistency with other data: the general tendency of increasing sediment hardness (grain size) as we move from west to east, which was evident in grab sample data, is also seen here. The area of soft sediments in the southeast corner is also found in both grab sample and echosounder data. QTC data shows some of the same features as the cluster processing, but the consistence is not particularly convincing.

Sediment properties (reflectivity and roughness) extracted from echosounder data

Some (mainly qualitative) information about sediment properties can also be extracted from simply inspecting the echo envelopes of echosounder returns. Figure 2.20 shows six characteristic echo envelopes measured at different locations (Figure 2.21) in the area. Signals 4 and 5 are close geographically, but have markedly different pulse shapes. Both have high energy (high reflectivity), but signal 5 has a much larger timespread than signal 6, indicating higher roughness. The high reflectivity in this area is consistent with TOPAS data. The data indicates high spatial variability in roughness. Signals 1 and 6 show a second maximum a few milliseconds after the main reflection, suggesting a second reflecting layer. The presence of a second layer is confirmed by TOPAS data for signal 1. (There are no TOPAS data for signal 6). Signal 3 has low energy and high timespread. TOPAS data (leg 02) indicates finely layered sediments in this area, which may explain this somewhat strange pulse shape.

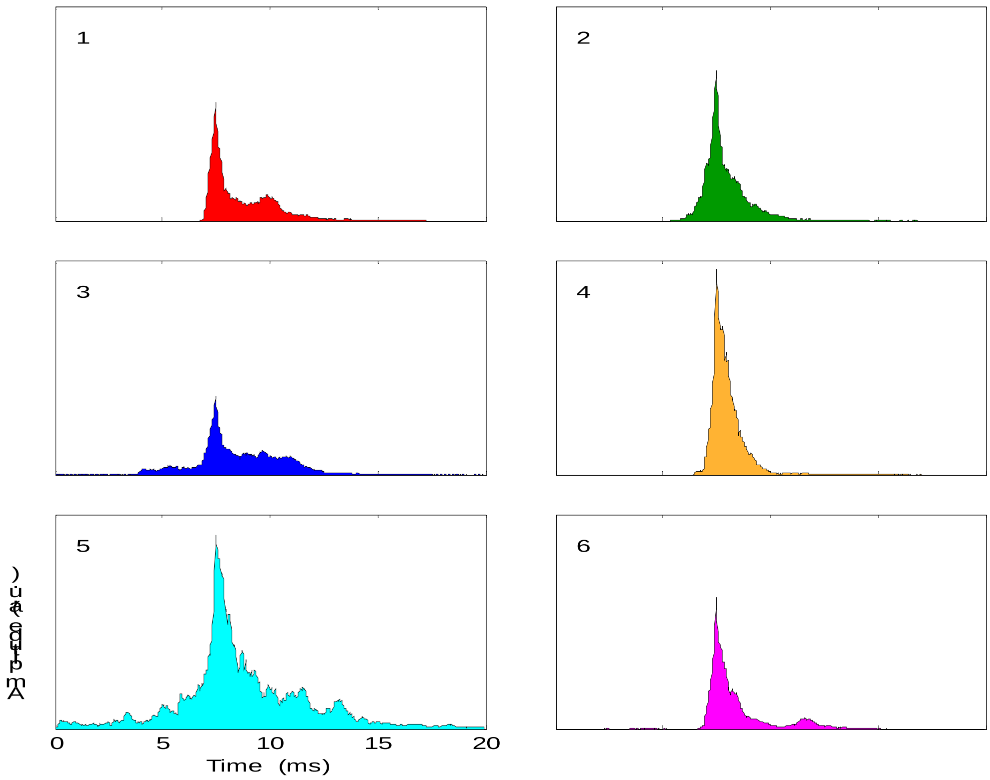

Figure 2.20 ([3] Fig. 4-20) Six characteristic echo envelopes from echosounder data. The locations of the measurements are indicated in Fig. 2.21 by circles in the corresponding colour. Each echo envelope is averaged over 20 (neighbouring) echoes.

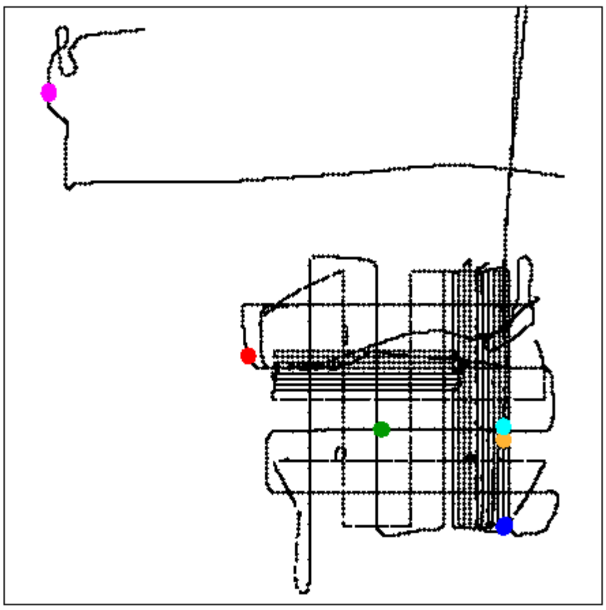

Figure 2.21 ([3] Fig. 4-19) Locations of the echo envelopes plotted in Fig. 2.20

Estimation of Low Frequency (LF) sediment properties from echosounder data and grab samples

In order to compare inversion results and ground truth, it is necessary to infer the relevant sediment properties from echosounder data. The compressional sound speed and density (c, ρ) of the sediment are derived through the following procedure from [3] Sec. 4.5:

1. Measure the (uncalibrated) acoustic reflection coefficient (R_{ac}) at vertical incidence and 38 kHz.
2. Obtain the calibrated acoustic reflection coefficient (R_{HF}) by comparison with grab samples. By using calibrated echosounder data this value can be measured directly.
3. Estimate grain size (M_Z) from the acoustic reflection coefficient (R_{HF}) using the APL-UW equations [3] p41. These equations describe properties of the top few cm of the sediment.
4. Estimate sediment properties (c, ρ) from grain size M_Z using the Bachman relations [3] p43. These equations give bulk sediment values.

$$\frac{c}{c_w} = \frac{1952M_Z^2 - 86.3M_Z + 4.14}{c_0}$$
$$\frac{\rho}{\rho_w} = \frac{2380M_Z^2 - 172.5M_Z + 6.89}{\rho_0} \qquad (2.1)$$

Here c_w, ρ_w are water sound speed and density at the bottom, and c_0, ρ_0 are reference values for temperature 23^{o}C and pressure 1 atm.

Sediment properties, such as density and sound speed, change quite rapidly with depth in the upper part of the sediment. This means that the impedance measured by an echosounder is a function of its penetration depth, and therefore of its frequency. The 38 kHz echosounder measures the impedance of the top 2-3 cm of the sediment. From this the grain size can be inferred using the APL-UW equations (valid for the top few cm). The grain size is then used to calculate the bulk sediment properties, using the Bachman relations (valid for 20-30 cm). The Bachman relations are more appropriate for the low frequency band of LFAS than the APL-UW equations. The main assumption is that the grain size does not vary with depth.

The procedure adopted for estimation of grain size from echosounder data automatically allows for vertical gradients in sediment properties, assuming that the grain size does not change with depth. If the bottom type changes with depth, as measured by grain size, this cannot be measured using a single frequency echosounder.

Mean grain size from echosounder data

The mean grain size, estimated from echosounder data by the procedure described above, is shown in Figure 2.23. The figure shows that surface sediment types in the area range from very fine silt (M_Z =7.6) to fine sand (M_Z =3). Along latitude 59.21 N grain size increases from west to east, in accordance with the grab samples. The actual grain sizes estimated from echosounder data appear to be slightly overestimated compared to grab samples. In the north-south direction there is also good correspondence between grab and echosounder data, with softer sediments in the southeastern corner of the grid.

On the basis of these results we conclude that there is good correspondence between echosounder data and grab samples, and that the echosounder measurements at 38 kHz are representative of the top few cm of the sediment.

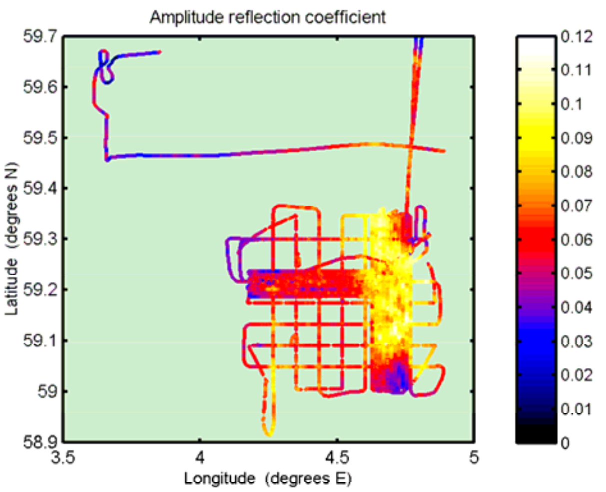

Figure 2.22 ([3] Fig. 4.23) Calibrated amplitude reflection coefficient for the echosounder.

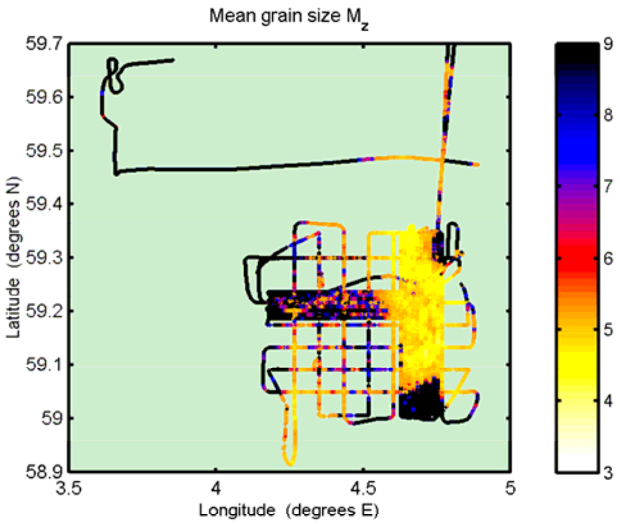

Figure 2.23 ([3] Fig. 4.24) Mean grain size computed from echosounder reflection coefficient.

2.4.4 TOPAS data

TOPAS is a sub-bottom profiler, using a hull mounted parametric source operating in the 2- 4 kHz range. Sub-bottom profiling was carried out along the six legs shown in Figure 2.12, at normal incidence. The survey speed was about 4 m/s.

Results from 3 sections

Figure 2.24 shows a section along TOPAS leg 5 running W-E along 59.27 N. There are thick upper sediments in the west, with some layering, the thickness gradually decreasing eastwards. The lower boundary of the upper layer is relatively diffuse in this region. As we move down into the depression, the layering becomes much more defined with a layer thickness of about 4 m. When we move up slope towards east, the upper layer seems to disappear. A second layer is also seen in parts of this section.

Leg 3, Figure 2.25, runs from N-S along the centre of the area. The bottom is flat and relatively homogenous along this section. The thickness of the upper layer increases slightly from N to S. The data may indicate a rough lower boundary. A second layer, with little structure, is clearly visible.

Leg 2, Figure 2.26, was a S-N run along 4.68 E. The leg passed close to a cluster of seamounts, and exhibits variable topography. A thin upper layer is found in most of the area, except in the southern part where the layer thickness approaches 20 m. Fine layering is visible in this part. The bedrock shows much more topographic variations along this leg than in the N-S direction (leg 3). Grab samples were collected along this leg.

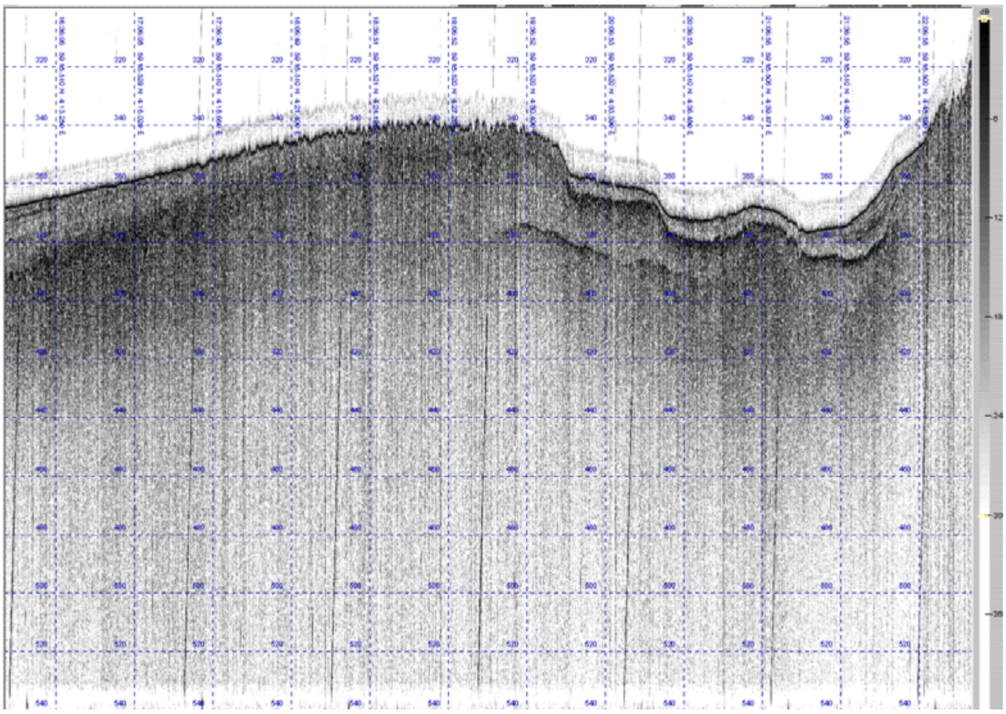

Figure 2.24 TOPAS leg 5, running W-E (left to right) along 59.27 N. Vertical resolution is 20 ms (two-way travel time) per division, corresponding to 15 m for a sound velocity of 1500 m/s. The horizontal tick mark spacing is 30 min.

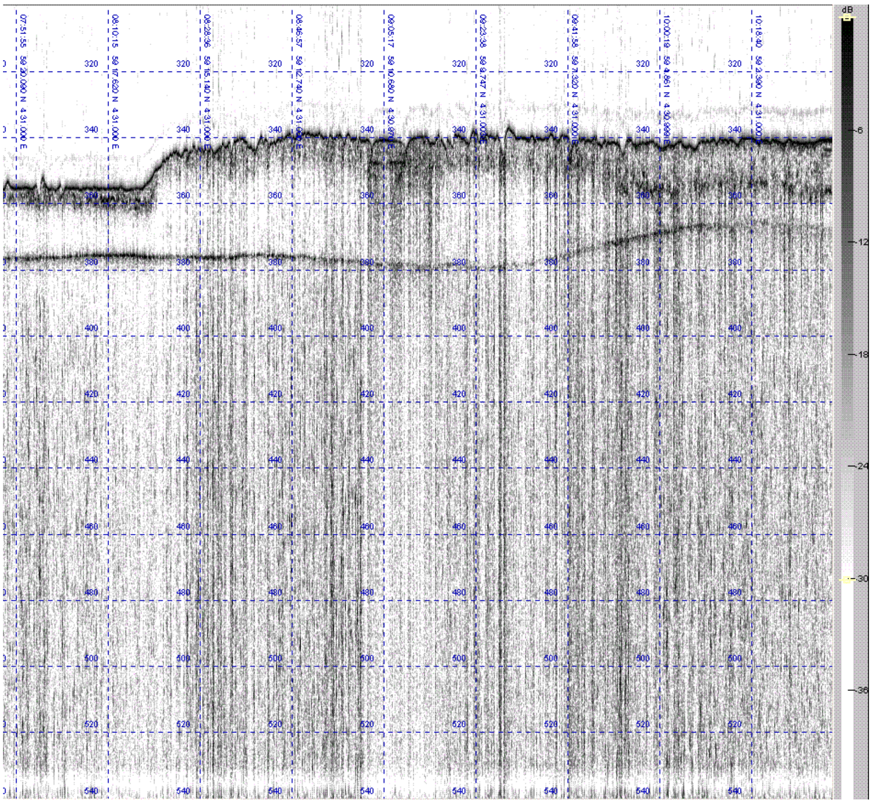

Figure 2.25 TOPAS leg 3, running N-S (left to right) along 5.59E. Vertical resolution is 20 ms per division. Horizontal tick mark spacing is 18.33 min, corresponding to about 4.4 km.

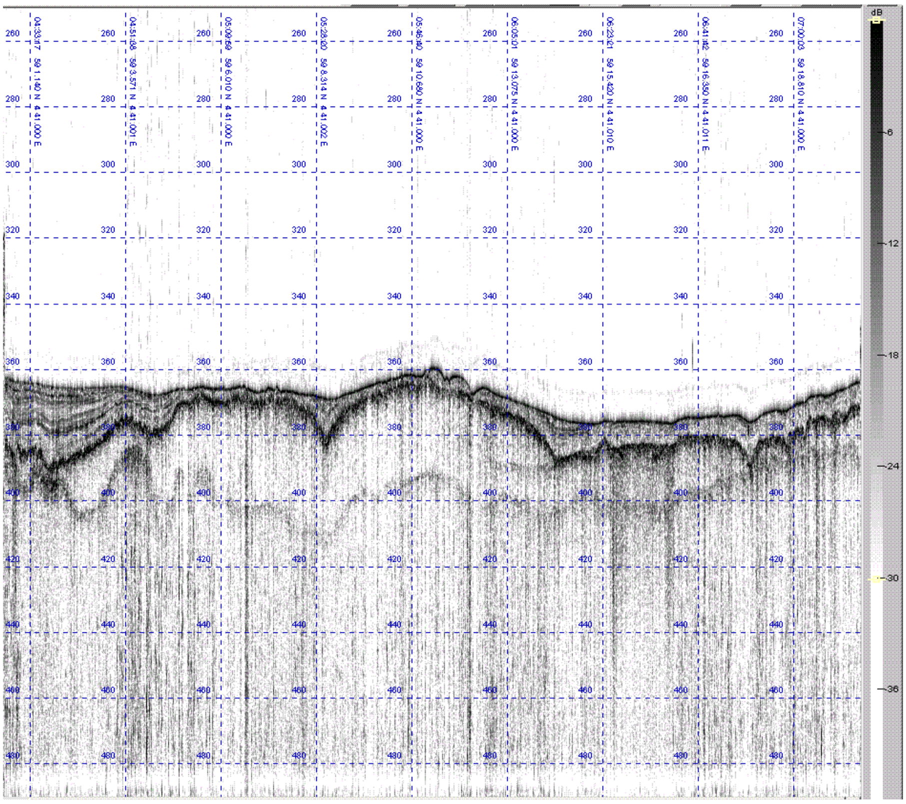

Figure 2.26 TOPAS leg 2, running S-N (left to right) along 4.68 E. Vertical resolution is 20 ms per division. Horizontal tick mark spacing is 18.33 min, corresponding to about 4.4 km.

The thickness of the upper soft sediment layer has been extracted from the data and is displayed in Figure 2.27. The plot is generated by first finding the layer thickness along each measurement leg (the yellow lines) and then fit a surface to the data by triangle-based linear interpolation. Thick sediments are found in west and southeast, thin sediments in the central to eastern part.

The layer thickness extracted from TOPAS data can be compared with the echosounder measurements of Figure 2.20. We observe that the echosounder suggests a 2 ms layer to the west of leg 5, while TOPAS seems to measure 10-15 ms in the same area. However, there is evidence of thinner layers in the western (left) part of leg 5, which is probably what we see in the echosounder data.

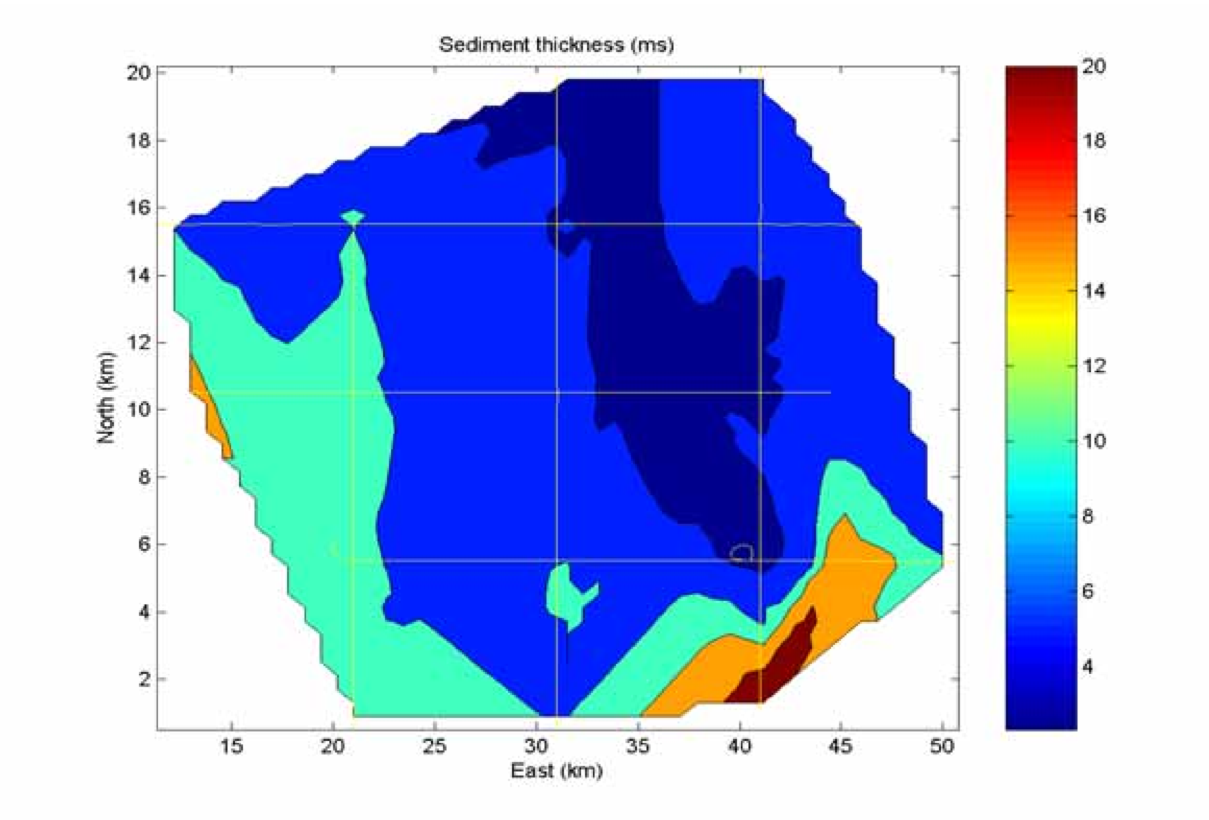

Figure 2.27 Thickness in ms of upper sediment layer extracted from TOPAS data. The axes denote distances (in km) north and east relative to position 59.00N 04.00E.

2.4.5 Best estimation

The inversion process yields the following parameters: the scattering strength μ, the sediment properties c, α and ρ, and the reflection loss parameter b. The parameters provided by ground truth measurements are: mean grain size (from grab samples) and acoustic reflection coefficient at normal incidence (from echo sounder). Hence, ground truth does not provide direct measurements of quantities that can be directly compared with the results of the acoustic inversion. What can be compared are derived quantities: through empirical relations it is possible to infer e.g. sediment sound speed and density from measured values of mean grain size and acoustic reflection coefficient, as was shown above. Some qualitative comparisons can also be made, by considering expected parameter correlations. Below we will show that reasonable estimates for sound speed and density of near-surface sediments can be estimated from ground truth. However, values of μ and α seems difficult to obtain. Whether the values obtained are representative for the bottom properties 'seen' by an LFAS is discussed in the next chapter.

Prior expectations

Geoacoustic parameters for the expected sediment types in the area, are given in [2] Sec. 6.2. Appendix B of [2] contains a summary of low frequency reverberation inversion and scattering measurements and provides values of μ for different bottom types.

Sound velocity and density

The physical properties of marine sediments such as density, sound speed, grain size and porosity are highly correlated with each other. Sound speed and density can therefore be estimated from the values of grain size measured by grab samples and echosounder. Figure 2.28 and Figure 2.29 show sound speed and density ratios obtained from the values of grain size in Figure 2.22, using the regression equations, Eq. (2.1). Sound speed and density are determined from the same quantity and therefore show the same features.

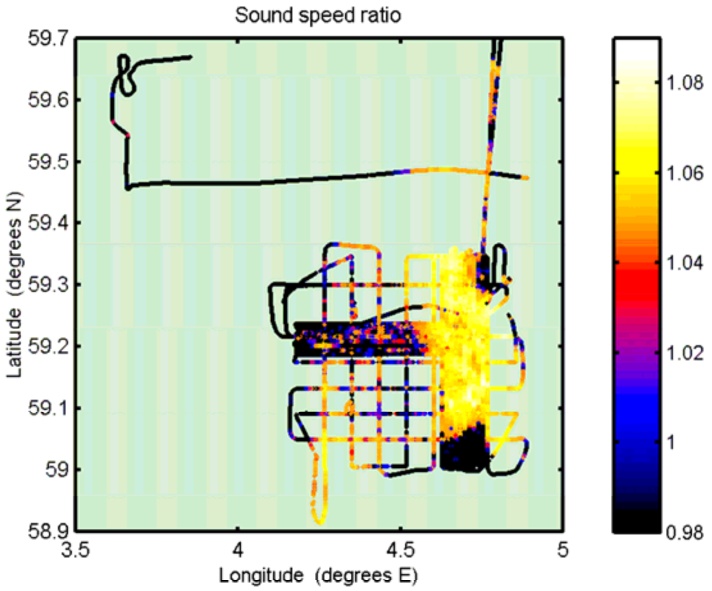

Figure 2.28 ([3] Fig. 4-25) Sound speed ratio derived from echosounder data.

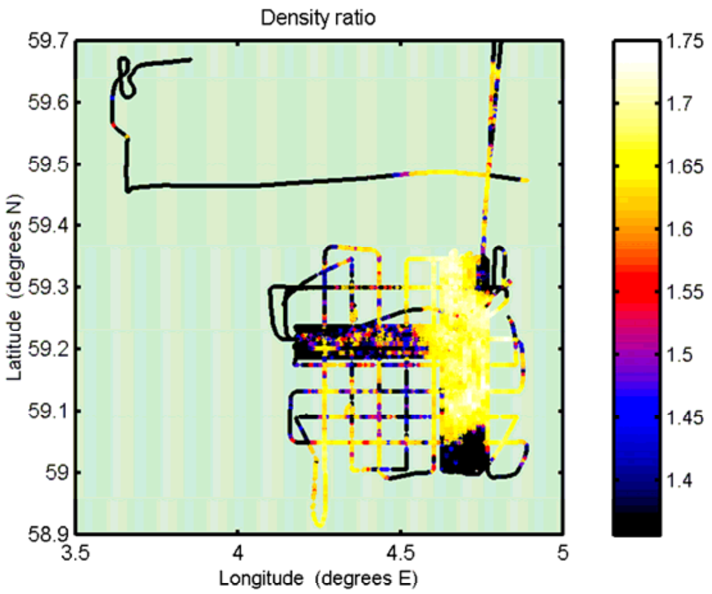

Figure 2.29 ([3] Fig. 4-26) Density ratio derived from echosounder data.

Scattering strength μ

It is difficult to measure scattering strength μ at low frequencies. To make a direct measurement of μ in shallow water, it is necessary to deploy a long vertical array. Such measurements are available at two locations in Vestfjorden (first sea trial), but not in the Norwegian trench (second sea trial). The question is whether μ can be estimated from available ground truth; grab samples and echosounder data.

Surface sediment type could be inferred from the values of grain size measured by grab samples and echosounder. However, we have not seen evidence of a correlation between surface sediment type and scattering strength μ at LFAS frequencies. Therefore, scattering strength μ cannot be inferred from grain size measured by echosounder.

The time spread of the echosounder signal is a measure of the roughness of the seabed. In principle, scattering strength at low grazing angles could be inferred from roughness amplitude. This approach is hampered by large uncertainties, as it is based on several assumptions: (i) roughness scattering is the dominant scattering mechanism (volume scattering and scattering from buried layers can be neglected), (ii) the roughness spectrum of the seabed must be known. However, the echosounder only gives information about the geographical variation of roughness, not actual roughness amplitudes. Scattering strength can therefore not be obtained from roughness measured by echosounder.

A direct measurement of scattering strength could be performed by a short-range measurement by LFAS, such as suggested in [7]. But the measurement requires longer separation between source and receiver than was used for the present experiments. Nor does it provide data at low grazing angles.

It may be mentioned that there are methods for estimating the roughness of the seabed from the properties of the specularly reflected pulse. A method called FARIM [17] estimates the roughness from the frequency shift it induces in the reflected signal.

Attenuation

Attenuation cannot be estimated from echosounder data. To measure attenuation we generally need many bottom interactions to accumulate sufficient sensitivity for this parameter. Attenuation is correlated with porosity or grain size. The relations are given in [1] Sec.4.5.2. However, this correlation is weaker than for sound speed and density, resulting in large uncertainties in the estimates. Reasonable bounds for attenuation may still be obtained from these relations.

Summary

Sediment types in the area:
The surface sediments in the area consist of clayey silt predominant in the centre, west and southeast, and sandy silt in the east and northeast. Sediment thickness varies considerably over the area. Thick, finely layered sediments are found in western and southeastern part, thin sediments are found in the central to eastern part.

Sound speed and density:
Sound speed and density ratios were obtained from echosounder reflection coefficient through empirical correlations with grain size. Sound speed ratio ranges from 0.98 to 1.09. For a sound speed in water of 1484 m/s this corresponds 1454 to 1615 m/s. Density is correlated with sound speed, and ranges from 1.35 to 1.75 g/cm^3.

Scattering strength and attenuation:
μ and α cannot be determined from the ground truth measured during the sea trials. Reasonable bounds for the parameters can be obtained from the literature.

Consistency between measurements:
Grain size inferred from echosounder is consistent with grab samples. No obvious inconsistencies are found in the area. This indicates that the sediment properties measured by echosounder are representative of the top few cm of the sediment layer.

3 ASSESSMENT OF THE INVERSION RESULTS

3.1 Comparison with Ground Truth

The inversion process yields the following parameters: the scattering strength μ, and the sound speed c, density ρ, and attenuation α of the sediment. These are the parameters of the local scattering and reflection loss models used in the inversion: Bottom scattering and reflection is assumed to obey the Lambert's rule and the Rayleigh reflection coefficient respectively. Scattering strength is therefore characterized by a single parameter μ (the Lambert constant), while the bottom reflection loss depends on three parameters (c, ρ and α).

Due to the inability of the inversion method to resolve the parameters c and α (Sec. 2.3.4), a reflection loss parameter b is provided instead of c, ρ and α. Reflection loss is given as $R=(b/\pi)\theta$, where θ is the grazing angle. This relation is an approximation to the Rayleigh reflection coefficient, and is valid for small grazing angles.

3.1.1 Results

Parameter correlations

Expected correlations:
There are physical reasons why one might expect a correlation between grain size and scattering strength ([1] Sec. 4.5.3). Unfortunately, in practice the correlations turn out to be very weak or non-existent. We would expect a correlation between LFAS scattering strength (μ) and echosounder timespread (a measure of roughness) as well as between LFAS reflection coefficient (π/b) and the normal incidence reflection coefficient measured by the echosounder (or grain size which is correlated to echosounder reflection coefficient). These correlations are considered below in Figure 3.1 and Figure 3.2.

LFAS scattering strength and grain size (Fig. 3.1):
Fig. 3.1.1-1 shows that there are no apparent correlations between LFAS scattering strength (μ) and mean grain size derived from grab samples and echosounder.

LFAS scattering strength and echosounder timespread (left panels of Fig. 3.2):
We observe that the very highest scattering strength values (white patches in bottom left graph) are associated with scattering from the vicinity of the seamounts. These show up as regions of long echo duration in the echosounder data (top left), consistent with our expectation.

There is also a region of high timespread and low scattering strength close to the southeastern corner of the area. In this region TOPAS data shows thick layers of finely layered sediments, which may explain this observation.

LFAS reflection coefficient and echosounder reflection coefficient (right panels of Fig. 3.2): As previously observed there is a general tendency for increasing LFAS reflection coefficient (π/b) from west to east, consistent with the higher normal incidence reflection coefficient (or grain size) observed from the echosounder. There are some instances of unusually high or low values of the parameter (π/b), for example close to leg 5. This is probably an artefact caused by local gradients in scattering strength. No other correlations are apparent. Overall, the correlation between surface sediment type (as measured by echosounder reflection coefficient) and LFAS reflection loss is weak.

In conclusion, there are some similarities between the inverted values of μ and b, and the output from the echosounder, but only for selected features. Overall the correlation between the outputs of the two systems is weak.

The lack of correlation between LFAS measurements and echosounder for scattering strength is not unexpected. After all, the systems are very different, using different geometries (horizontal versus vertical) and operating frequencies (1.5 kHz versus 38 kHz). The incidence angles, penetration depths and averaging over depth and range are therefore completely different for the two systems. Despite the differences between the systems, we had expected a stronger correlation between low frequency reflection loss and bottom type than was observed.

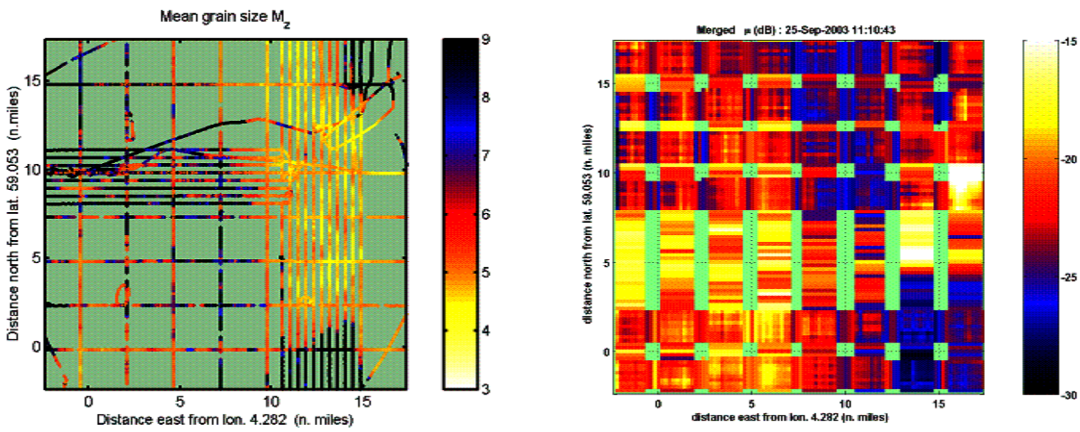

Figure 3.1 Comparison of LFAS scattering strength (right panel) with mean grain size derived from echosounder data and grab samples (left panel).

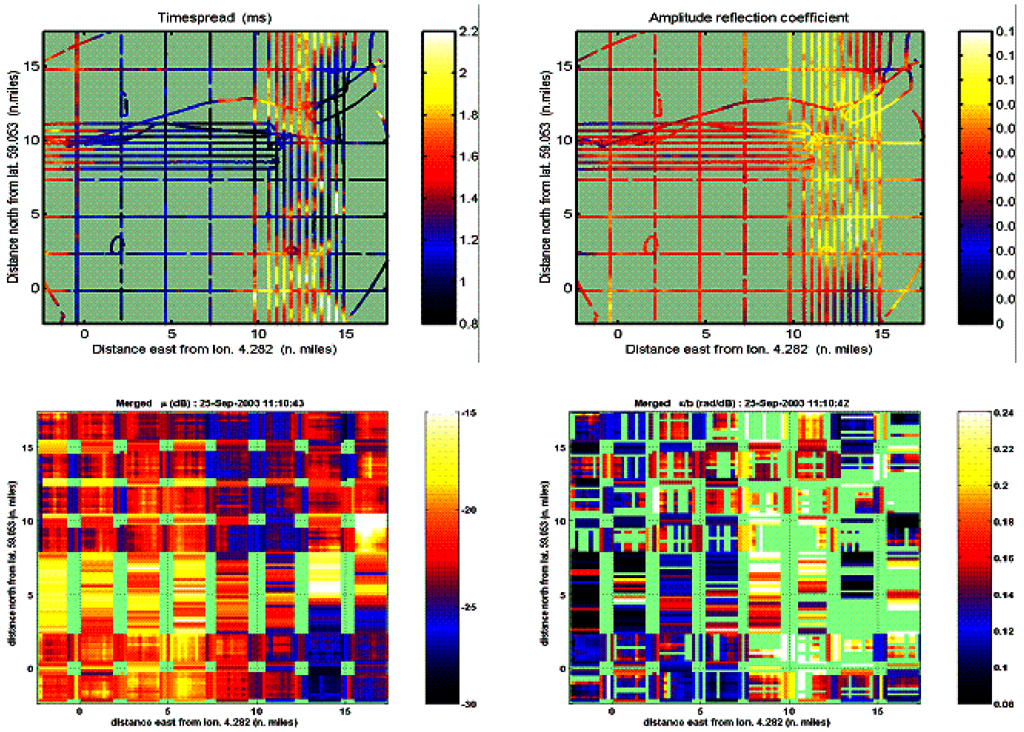

Figure 3.2 ([3] fig 6-36). Comparison of echosounder data (top left=echo duration; top right=acoustic reflection coefficient) with LFAS inversion results (bottom left=scattering strength μ; bottom right=reflection coefficient π/b)

Scattering strength parameter μ

Due to the unknown calibration factor of the CAPTAS processor it is not possible to make conclusions concerning the absolute value of the scattering strength.

Variation of μ:

Changes in scattering strength up to about 15 dB have been observed in the area. The bottom types in the area ranges from thick layers of silty clay to crystalline bedrock covered by thin layers of fine sand. Such variations are therefore to be expected.

Effects of range dependence of parameters:

The observed variation of scattering strength may be partly due to local bottom slope. A flat bottom has been assumed for the inversions, which means that an upsloping bottom will be compensated by too high scattering strength.

Features observed in the reverberation curves may be caused by local changes in scattering strength, but may also be caused by propagation effects (focusing and variations in reflection loss). In a range independent case such variations in a parameter must be absorbed by a single value.

Azimuthal anisotropy:
Scattering strength shows azimuthal anisotropy in the western half of the area. The observed anisotropy is consistent with the presence of glacial scouring in the area, running in the N-S direction. The scattering strength is up to 4 dB higher looking across iceberg scouring marks (east-west direction) than looking along them (north-south direction).

Correlation with ground truth data:
There is no obvious correlation between the scattering parameter μ measured at the LFAS frequency (1.5 kHz) and echosounder measurements (grain size and time spread). The lack of correlation suggests that the properties of near-surface sediments are a poor indicator of scattering strength for low frequency, long-range systems.

Reflection loss parameter *b*

There is a weak correlation (some similarities, but only for selected features) between LFAS reflection coefficient (π/b) and grain size derived from echosounder measurements. The reason for the correlations being so weak could be that we are unable to measure the parameter b with sufficient precision.

Sediment sound speed and attenuation

Inverted values of sediment sound speed and attenuation are consistently higher than expected for the actual bottom types. An average inverted value for sound speed is 1700 m/s, while the values expected from bottom type ranges from 1454 to 1615 m/s. Part of the reason for the discrepancy is the presence of a second reflecting layer a few metres beneath the water-sediment boundary, as shown by TOPAS data. However, there are also discrepancies in regions with a thick sediment layer.

Reasonable values of attenuation for low frequency propagation cannot be determined from a local measurement. Attenuation requires LFAS measurements. Attenuation can be caused by several loss mechanisms.

3.1.2 Some challenges in validating inversion results against ground truth.

Validating the results of the inversion against ground truth is not straightforward. Questions about the quality of ground truth, and how representative the (usually sparse) samples are for the area will always arise. Some challenges related to the validation process are:

- How representative are the ground truth samples. Shallow samples may not capture important vertical structure, and low spatial sampling does not capture the true geographical variability of the area.
- The ground truth data may not be the quantities provided by the inversion. In our case ground truth does not provide direct measurements of the parameters provided by the inversion. The best we can do is to compare derived quantities as well as look for expected parameter correlations.
- Ground truth is measured at different frequencies, incidence angles and with different averaging in range and depth than inversion results.

- The inversion provides the best parameters for the selected models. True bottom parameters can therefore not be found unless the selected models include the most important scattering/reflection mechanisms.
- The inversion method is likely to produce an effective (or equivalent) bottom model, and not the true geophysical parameters.

Vertical structure

The CAPTAS measurements are sensitive to seabed properties down to a few meters depth, while the ground truth measures the properties of the upper few cm of the sediment layer. The procedure used for estimating sediment properties automatically accounts for vertical gradients in sound speed and density in the sediment, under the assumption that the bottom type does not change with depth. Any variation of bottom type (grain size) with depth is therefore not captured by the grab samples. In the case of thin surface sediments, deeper layers may also influence CAPTAS results.

Spatial sampling and averaging

CAPTAS results are averaged over horizontal range while grab samples are point measurements. (Reverberation received at a given instant comes from many bottom patches that share the same path length). Although grab samples are sparse, they are extended by echosounder data to cover the entire ship track. The horizontal sampling is therefore relatively good.

3.2 Comparison of predictions with and without inversion results

A number of software tools exist which allow estimation of sonar performances, many countries or companies have developed their own tool such as VENUS in France (developed by Thales Underwater Systems), LYBIN in Norway (developed by NDLO/Sea) and ALMOST in the Netherlands (developed by FEL-TNO). These tools are usually connected to environmental databases, which provide the necessary input data to run acoustic models like propagation and reverberation models. Of course, the quality of the prediction is determined by the quality of the available environment data and the main objective of the RUMBLE project is to propose a methodology to improve our knowledge of bottom geo-acoustic parameters. One way to assess the improvement brought by the RUMBLE project is to compare the quality of the prediction with and without results from RUMBLE. This is done in this section.

The quality of the prediction is evaluated by comparing predictions to measurements and since what has been measured in the project is beam (broadside) reverberation power decay versus time, the same quantity is also predicted by two independent models: VENUS and LYBIN. It was not possible to measure echo to reverberation ratio or probability of detection since no controlled target was present during sea trials but it was not necessary since the main uncertainty concern bottom properties, which translates directly into reverberation level and decay curves.

One can remark that because bottom properties are obtained by inversion from measured reverberation curves, predictions using inverted bottom parameters will necessarily match experimental data better than predictions made with other bottom data, they will provide by construction the best match if the direct model used for prediction is the same as the one used for inversion. Therefore, inversion should necessarily bring some improvement; in the following sections, we are trying to assess the importance of this improvement by using two existing sonar performance models: VENUS and LYBIN.

3.2.1 Predictions with VENUS

Venus is a performance prediction model developed by TUS. Detailed information on the model can be found in RUMBLE technical report DE08 (Technical report on detection performance model) [19]. The software incorporates bottom data concerning:

- Bottom topography: gridded data from ETOPO2 (grid size 2’ in longitude and latitude) + GEBCO iso-depth contours (see Figure 3.3)
- Sediment nature: TUS database called GAEDS elaborated from published data (see Figure 3.4)

The accuracy of these existing GAEDS data in the second experimental area is of course questionable and unknown.

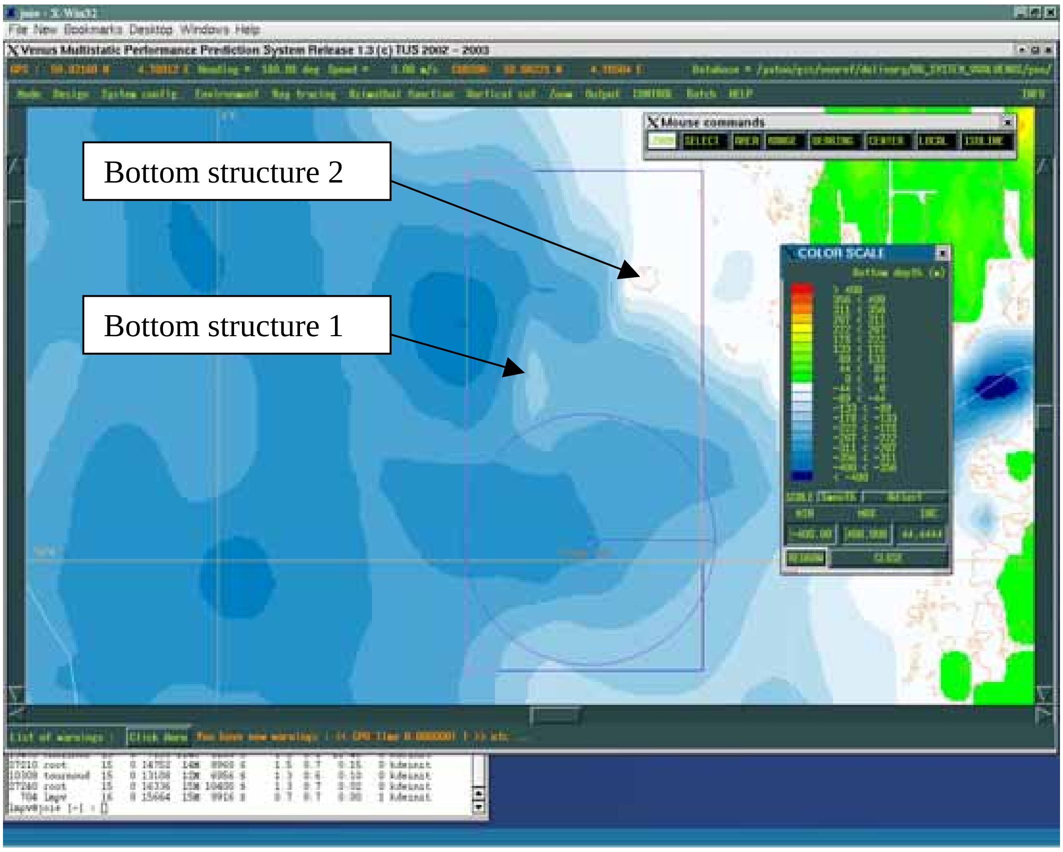

Figure 3.3 Bottom topography available in VENUS corresponding to second experiment area.

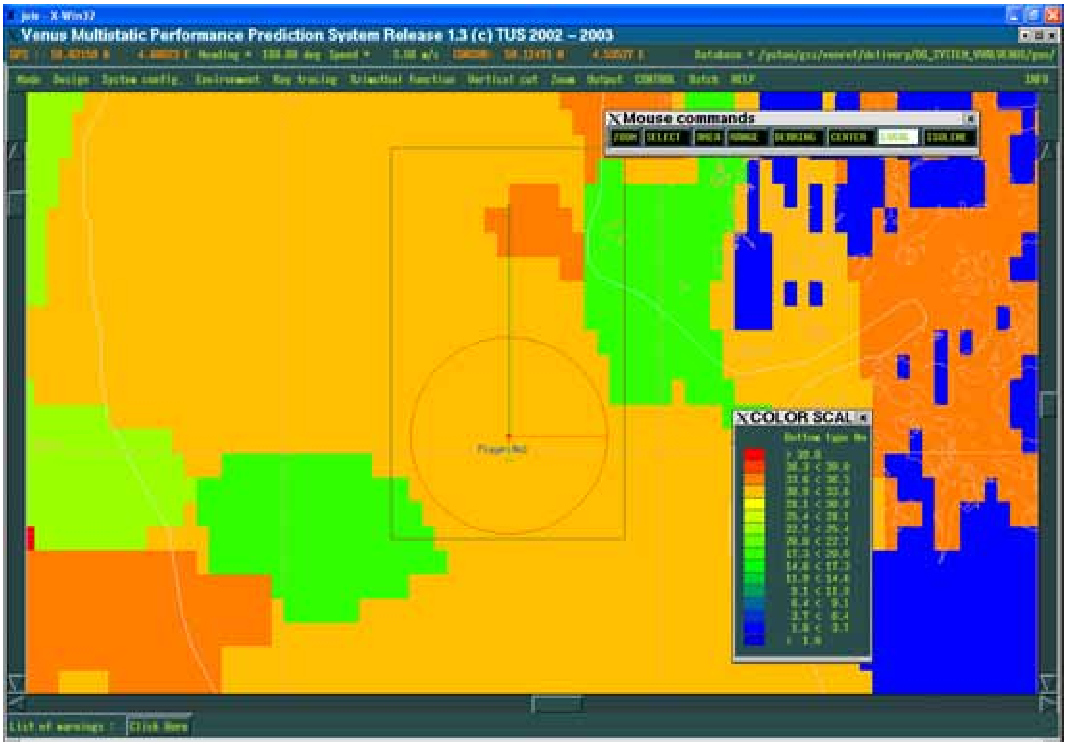

Figure 3.4 Sediment type available in VENUS corresponding to second experiment area (green – coarse sand, light brown – mud, dark brown – sandy mud)

The sonar (SOCRATES source and CAPTAS receiving array) is simulated in VENUS using only the left and right broadside beams for which experimental results are available.
The reverberation is modelled by splitting the whole 3D medium surrounding the sonar into 36 horizontal sectors of 10° width in which range dependent propagation characteristics (multipaths) are computed in the centre of each sector, considering these characteristics do not change within the 10° sectors. In order to predict reverberation (surface, bottom and volume) at a beam output, reverberation power versus time is accumulated by sweeping on all sectors and weighting by the beampattern in each sector, including side-lobes. Local scattering is modelled using:

- Chapmann-Harris model with sea state 2 for surface reverberation in all cases,
- Constant scattering index of – 80 dB/m3 for volume reverberation.
- Lambert's rule for bottom reverberation, the same model which has been used for inversion by TNO

In the following, we compare the reverberation power decay curves corresponding to:

- Experimental
- Predictions by VENUS using standard GAEDS data
- Prediction by VENUS using the RUMBLE bottom (μ parameter for reverberation, c and α for Rayleigh reflection coefficient obtained from the inversion process).

The topography of the RUMBLE bottom has been obtained from the echo-sounder information recorded along all legs and interpolation between legs (see Figure 3.5 which is with the same colour scale as Figure 3.3).

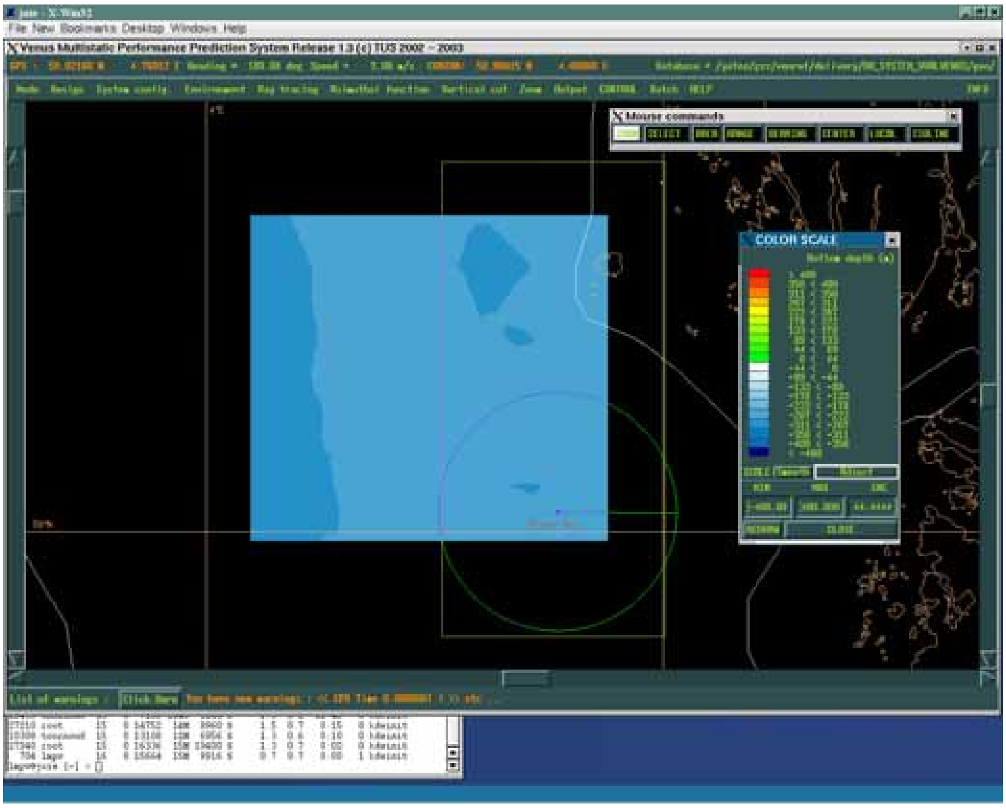

Figure 3.5 RUMBLE bottom topography from echo-sounder data.

It can be noticed already that there is significant difference between the VENUS chart and the RUMBLE chart.

Different legs have been analysed:

- Leg 6 (North to South),
- Leg 11(North to South), closer to coast.

The following figures (Figure 3.6 to Figure 3.15) show reverberation levels coded in colour versus time after transmission on the vertical axis and ping number on the horizontal axis. Because of the calibration problem, VENUS results have been corrected by applying a global shift in dB in such a way that the mean dB value obtained by integration on all the picture equals the similar mean value obtained with the corresponding experimental results.

VENUS Results from Leg 6

VENUS bottom:

VENUS simulation of left broadside beam (looking towards the coast) is presented on Figure 3.6, while the measurement is presented on Figure 3.7.

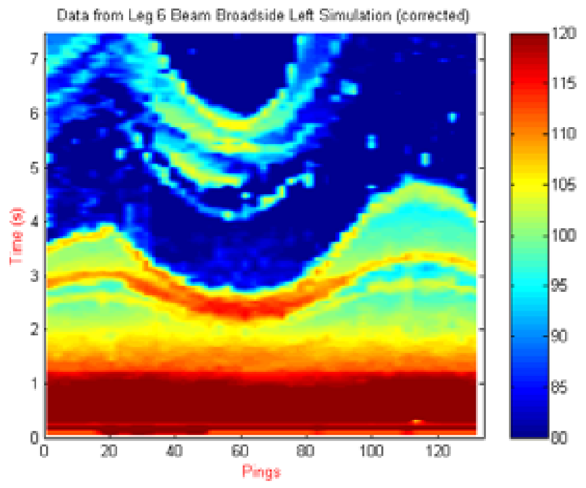

Figure 3.6 VENUS simulation using VENUS bottom – Leg 6, left broadside beam.

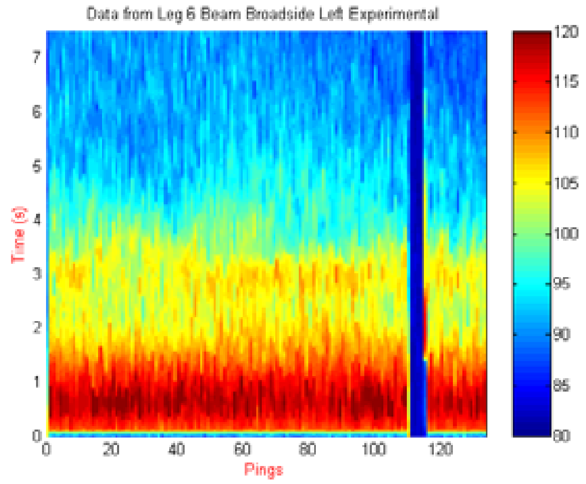

Figure 3.7 Measured - Leg 6, left broadside beam.

The difference between prediction and measurement is quite important. The prediction exhibit higher levels and also a clear structure around ping 50, which is due to a bottom structure (bottom structure 1 of Figure 3.3), which is not present in the RUMBLE bottom. The difference in dB is displayed on Figure 3.8, it amounts to 10 dB and more.

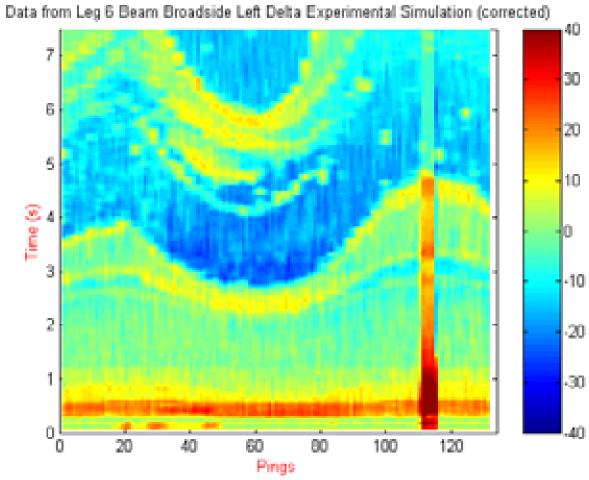

Figure 3.8 Difference [Simulated with VENUS bottom– Measured] - Leg 6, left broadside beam.

RUMBLE bottom:
VENUS is now run with the RUMBLE bottom (both topography and geo-acoustic parameters). The results are as follow (Figure 3.9):

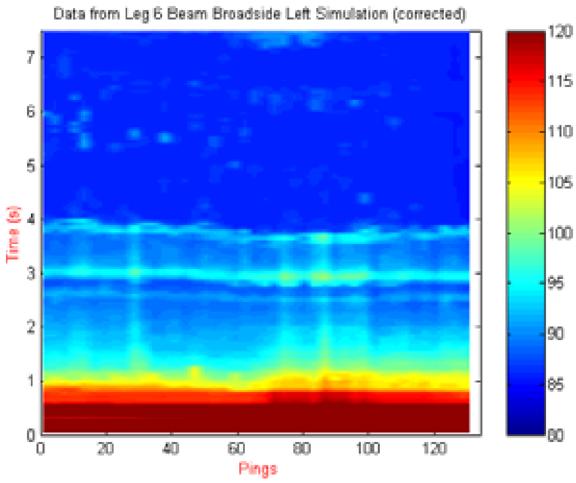

Figure 3.9 VENUS simulation using RUMBLE bottom - Leg 6, left broadside beam.

This result is to be compared with the corresponding measurement displayed on Figure 3.7. One can see that the simulation is much closer to the measurement although the simulation shows a faster decay compared to measurement (it was the opposite with VENUS bottom), furthermore, the structure observed on Figure 3.6 corresponding to a bottom structure cannot be seen any more because there is no bottom structure in the RUMBLE bottom.
The difference between simulation and measurement is displayed on Figure 3.10, showing a difference of less than 6 dB except on the first half second.

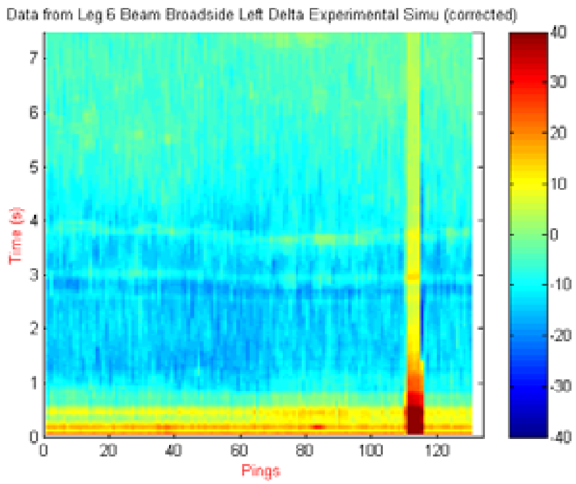

Figure 3.10 Difference [Simulated with RUMBLE bottom– Measured] - Leg 6, left broadside beam.

VENUS Results from Leg 11

The same type of analysis was carried out on Leg 11, which is parallel to Leg 6 but closer to the coast.

VENUS bottom:

VENUS simulation of left broadside beam (looking towards the coast) is presented on Figure 3.11 while the measurement is presented on Figure 3.12.

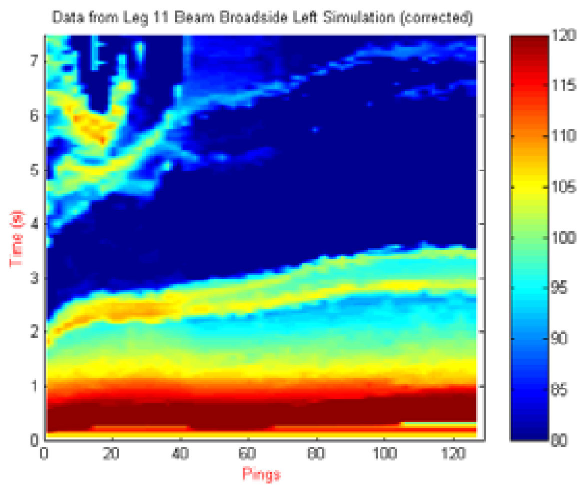

Figure 3.11 VENUS simulation using VENUS bottom – Leg 11, left broadside beam.

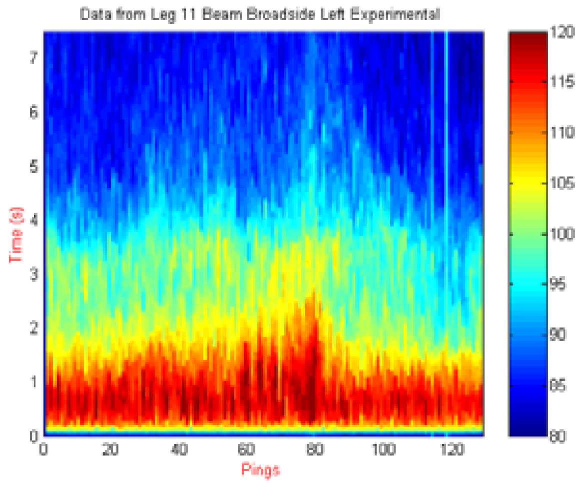

Figure 3.12 Measured - Leg 11, left broadside beam.

The difference between prediction and measurement is quite important like with Leg 6. The prediction exhibit higher levels and also a clear structure around ping 20, which is due to a bottom structure (bottom structure 2 of Figure 3.3). This structure, like in the case of Leg 6, is not present in the RUMBLE bottom. The difference in dB is displayed on Figure 3.13, it lies roughly between 10 and 20 dB.

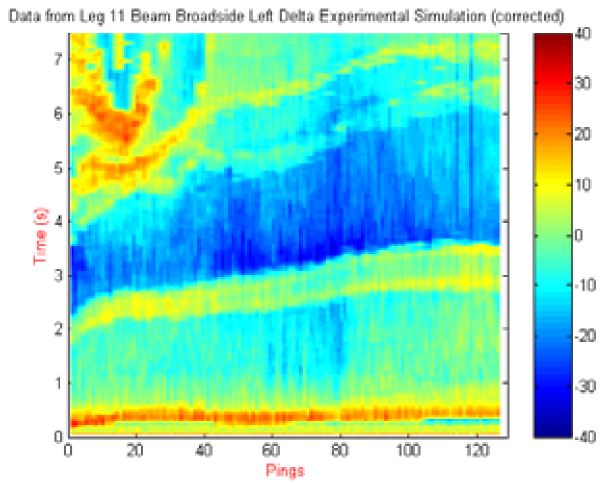

Figure 3.13 Difference [Simulated with VENUS bottom– Measured] - Leg 11, left broadside beam.

RUMBLE bottom:

Like for Leg 6, VENUS is now run with the RUMBLE bottom (both topography and geo-acoustic parameters). The results are as follow (Figure 3.14)

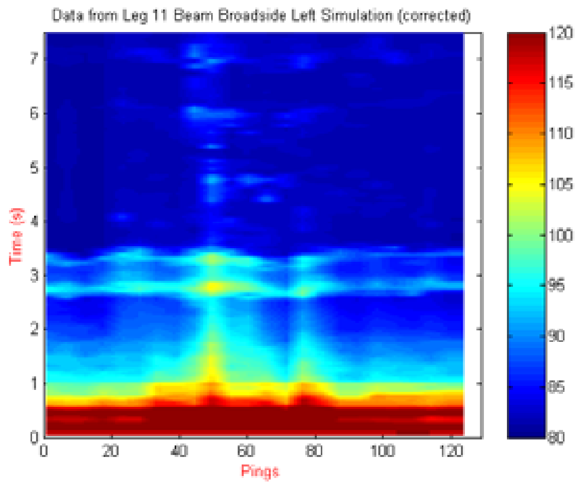

Figure 3.14 VENUS simulation using RUMBLE bottom - Leg 11, left broadside beam.

This result is to be compared with the corresponding measurement displayed on Figure 3.12. Here again the simulation is much closer to the measurement; the high level reverberation band seen all along the leg at 3 seconds after transmission is recovered in the simulation, and also the high level zone around ping 80. The structure observed on Figure 3.11 around ping 20 corresponding to a bottom structure cannot be seen any more because there is no bottom structure at this place in the RUMBLE bottom.

The difference between simulation and measurement is displayed on Figure 3.15 showing a difference of less than 6 dB except on the first half second, very similar to Leg 6.

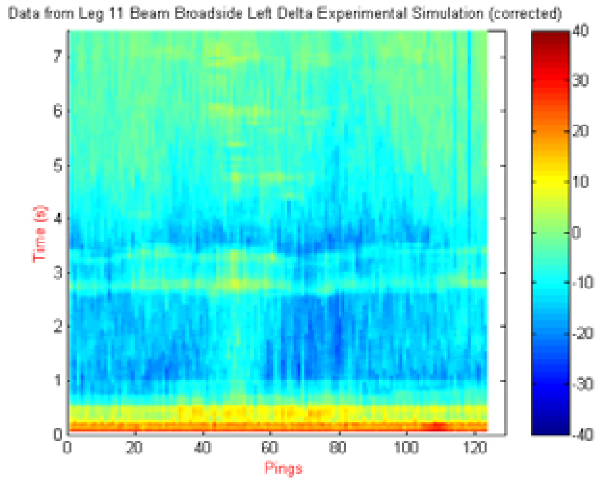

Figure 3.15 Difference [Simulated with RUMBLE bottom– Measured] - Leg 11, left broadside beam.

Conclusion on VENUS predictions

It has been shown that using the RUMBLE bottom rather than the standard VENUS bottom improves significantly the prediction of the reverberation level at middle range (few seconds). It is not possible at this stage to separate the effects of a better knowledge of bottom topography or a better knowledge of bottom geo-acoustic properties. Altogether the improvement amounts to about 10 dB, it can be higher in specific places.

3.2.2 Predictions with LYBIN

LYBIN is a 2D ray-trace model developed by NDLO/Sea.
For the comparison LYBIN was first run with its standard models for bottom backscattering and reflection loss, and then with the models obtained from RUMBLE results. In both cases a flat bottom was used, with water depth set to the water depth at the source for each ping.
The standard models for bottom reflection loss and backscattering strength used in LYBIN are FNWC and McKinney & Anderson respectively.

The RUMBLE bottom model

Bottom reflection loss:
The Rayleigh reflection coefficient with parameters determined by the procedure in Sec. 2.1.1 is used. (Use a fixed sound speed and compute values of attenuation and density consistent with the inverted reflection loss parameter) Sediment sound speed is set to 1675 m/s, as recommended in [3] Sec. 6.7. This sound speed value is the median of the values obtained by the inversion. The value is probably too high, but gives the correct reverberation using TAMAR. Whether it works equally well for other models depends on the consistency between the forward models of reverberation.

Scattering strength:
Lamberts rule with scattering strength parameter μ obtained from inversions. The values are corrected by an empirical calibration coefficient, [3] Sec. 3.2.

Runs

Leg 7 and 11 were considered for this study (data only available for these runs). Leg 7 runs in N-S direction over an area of uniform water depth and bottom type. Leg 11 runs in S-N direction over an area of variable bathymetry, close to the seamounts in the eastern part of the area.

For the reverberation predictions we used the same environment (sound speed profile and water depth) as was used for the inversions. A ping-average over 5 consecutive pings is applied to the output.

Results for leg 7

Figure 3.16 shows a comparison between reverberation predictions using the RUMBLE bottom model and measured reverberation for leg 7. There is an offset in absolute level due to unknown calibration. Apart from that, there is quite good agreement between the shapes of modelled and measured reverberation curves; the slopes of the curves are approximately the same, and the model also reproduces the area of high reverberation at 2.5-4 s.

However, the model also predicts an area of high reverberation at 6-8 s (a multiple of the caustic at 3 s) that is not seen in the data. A possible explanation why this feature does not appear in the data is that the seabed acts as a diffuse scatterer. This means that there is no well-defined cycle distance for the caustic rays, and therefore no second peak.
High reverberation can be a feature, but it can also be a focusing of energy due to the sound speed profile. The area of high reverberation that is missing in the measured data is obviously a propagation effect.

Figure 3.17 shows a comparison between reverberation predictions using the RUMBLE bottom model and LYBIN standard bottom models. LYBIN bottom types 1, 2 and 3 correspond to gravel, sand and silty sand respectively. The bottom type determined from grab samples corresponds to LYBIN bottom type 3. However, previous measurements in the area have shown that LYBIN bottom type 2 gives good predictions for the area. The figure shows that (i) reverberation levels for LYBIN bottom type 2 and the RUMBLE model match well at short ranges, (ii) the RUMBLE model predicts slower reverberation decay with range than the LYBIN models, and (iii) LYBIN bottom type 3 predicts too low reverberation. LYBIN bottom model 2 underpredicts reverberation by some 8 dB in the range of 4-9 s, while the average error for LYBIN bottom type 3 is 20 to 25 dB.

For the RUMBLE bottom model, the spread in modelled reverberation for ranges up to about 2.2 s is determined by the spread in μ. The spread for the LYBIN standard models is due to variations in water depth for the different pings.

Results for the starboard beam are very similar to port beam for leg 7. This is expected since the region around leg 7 has a uniform, featureless bathymetry.

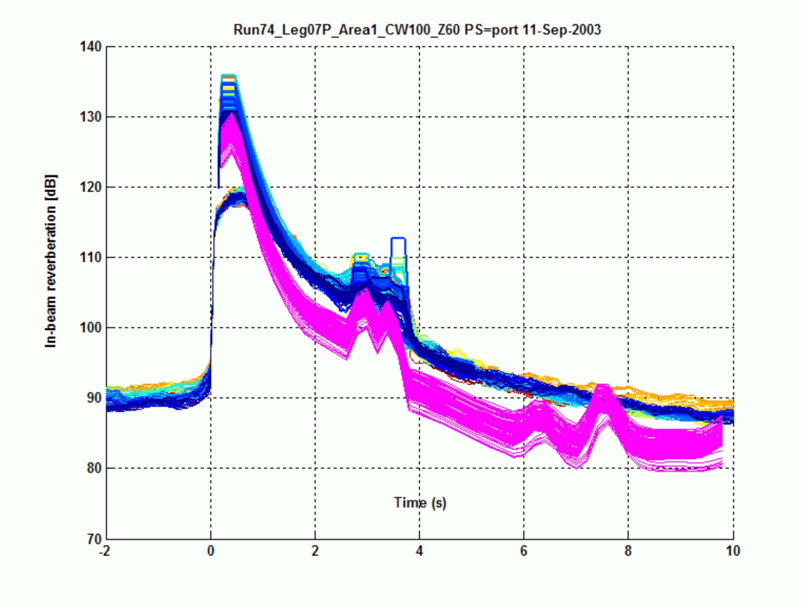

Figure 3.16 Measured reverberation versus time in the broadside beam, and reverberation predicted by LYBIN using RUMBLE bottom model. Data from leg 7, port beam.

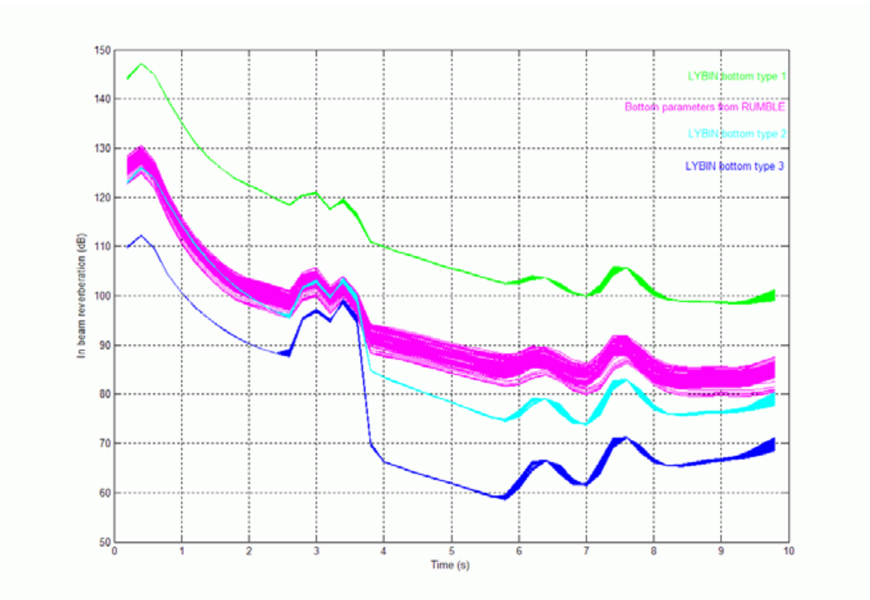

Figure 3.17 Reverberation predicted from the RUMBLE bottom model (pink curves) and LYBIN bottom types 1,2 and 3. Leg 7, port beam.

Results for leg 11

Leg 11 is a repeat of leg 5, this time in S-N direction. There is much more structure in the reverberation curves for leg 11 than for leg 7 as shown in Figure 3.18 and Figure 3.19. There are also significant differences between port and starboard beam as shown in Figure 3.20 and Figure 3.21.

The improvements in reverberation prediction by using RUMBLE results are somewhat smaller for leg 11 than for leg 7. Bottom type 2 underpredicts reverberation by about 6 dB, and bottom type 3 by some 20 dB. LYBIN bottom type 2 matches data better for leg 11 than for leg 7.

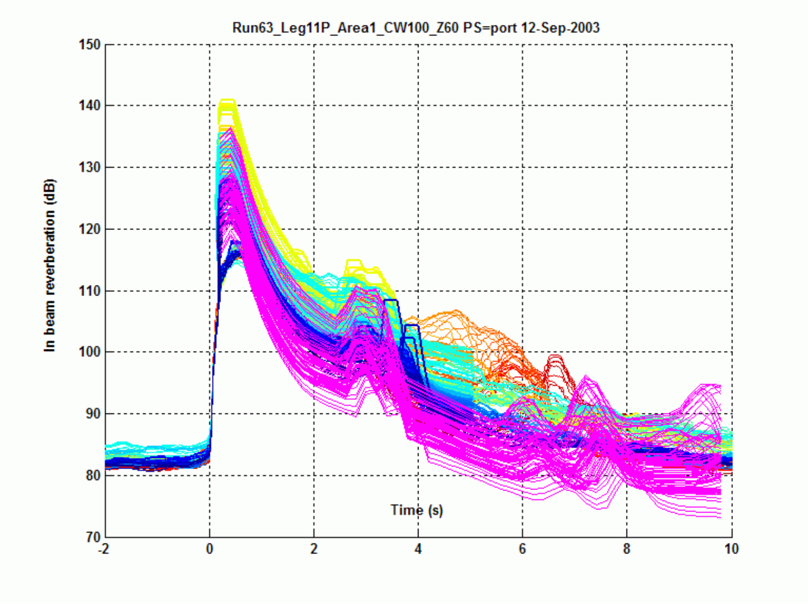

Figure 3.18 Measured reverberation versus time in the broadside beam, and reverberation predicted by LYBIN using RUMBLE bottom model. Data from leg 11, port beam. The curves are colour coded according to ping number.

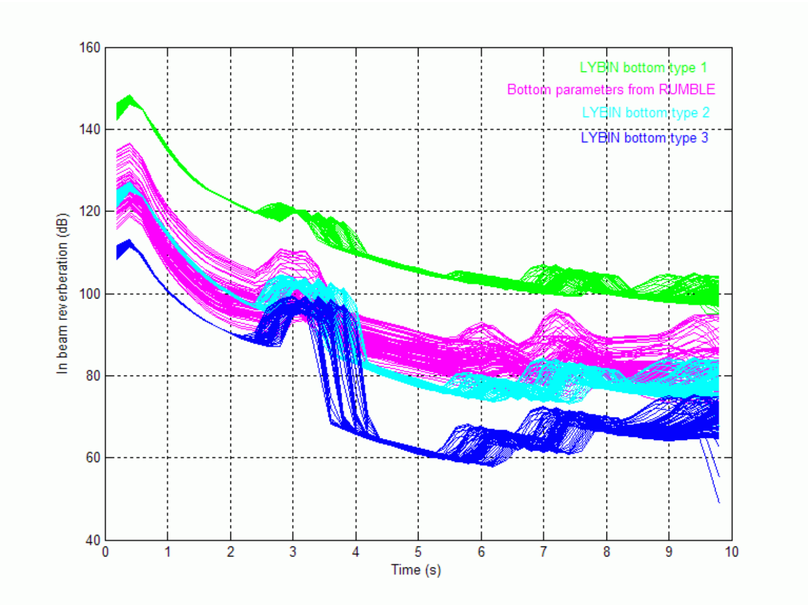

Figure 3.19 Reverberation predicted from the RUMBLE bottom model (pink curves) and LYBIN bottom types 1,2 and 3. Leg 11 port beam.

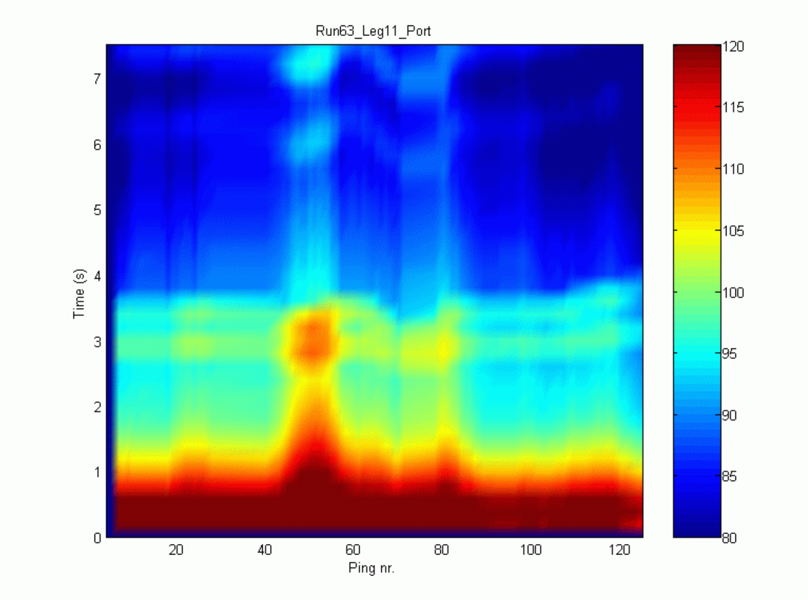

Figure 3.20 Reverberation predicted by LYBIN for port beam along leg 11

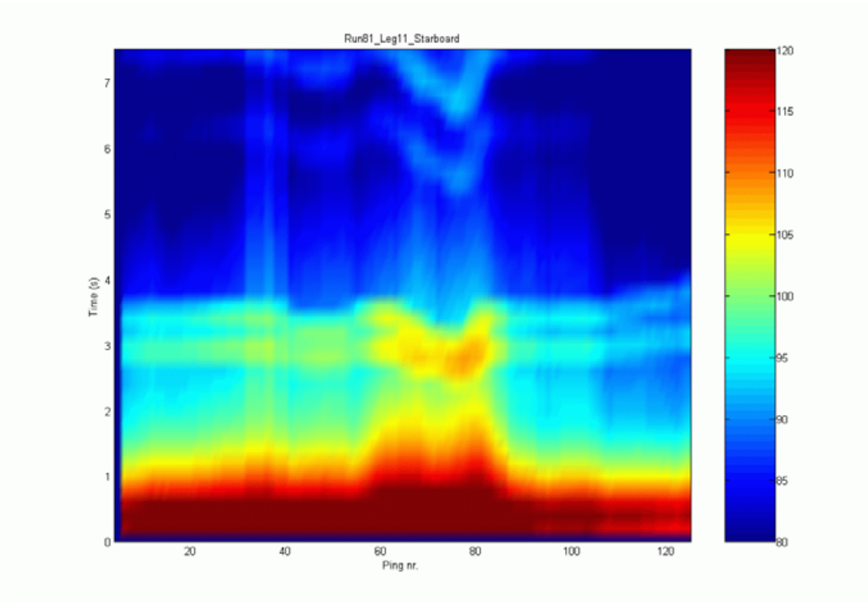

Figure 3.21 Reverberation predicted by LYBIN for starboard beam along leg 11

Conclusion on LYBIN predictions

The two reverberation models applied for the study, VENUS and LYBIN, produce, on the average, comparable results. However, there are differences in the details of the predictions. The differences are partly due to model differences, and partly due to the slightly different bottom topography that were used in the models.

Significant improvements in reverberation prediction are achieved by using the RUMBLE bottom model rather than the standard LYBIN bottom models. The improvements achieved depend on the character of the area and on our previous knowledge of the bottom properties of the area. With good previous knowledge of the area the overall improvement is in the order of 6 to 10 dB. However, in a less known area the improvements may well be much higher, in the order of 20 dB.

An important finding from the LFAS measurements was that large changes in scattering strength μ were observed in areas, which from previous knowledge would have been categorized by a single value of μ. This means that the improvement estimated above, in the case of a known area, is probably too optimistic. A more realistic estimate of the error, taking into account the inherent variability, is at least 10 dB, even in an area where measurements are available.

4 ASSESSMENT OF THE INVERSION METHOD

4.1 Reasonable swath range

The swath range that can be obtained depends on many factors. Bottom type, wind conditions, sound speed profile, depth of sonar and the transmitted pulse will all influence the swath width. For the first sea trial the transmitted signal consisted of two pulses: a 10 ms CW at 1.5 kHz followed 4.9 s later by a 4.9 s Hyperbolic FM (HFM) pulse from 1 to 2 kHz. During the experiments a reduced source level, 205.5 dB re 1 μPa @ 1m, was used. The full power of the SOCRATES source is 209 dB re 1 μPa @1m. Inversions were carried out for the 10 ms CW signal. For the second sea trial a long (100 ms) CW pulse was used in addition to the short 10 ms pulse. A longer time delay was also inserted between the pulses, to increase the time window that can be exploited for the inversions. Inversions were carried out for the long (100 ms) CW signal only.

Swath range obtained in first sea trial

For the first sea trial the available time window for reverberation measurements (from the 10 ms CW pulse) was 1 to 3.5 km, limited above by the onset of the HFM pulse. The maximum range was limited by SNR at a much shorter range, due to the low signal energy in the transmitted pulse. For ranges less than 1 km a bistatic geometry would be required.

Swath range obtained in second sea trial

The swath range obtained in the second sea trial was 1 to 3.7 km due to the increased signal energy in the 100 ms CW pulse.

Swath range for high energy HFM pulse

The high-energy HFM transmissions have not been analysed. The maximum swath range that can be obtained by the system has therefore not been established. The reasons for not analysing long range data were that our first priority was to demonstrate successful inversion of short range data, and that insufficient long-range SSP data would have caused problems with the interpretation of the long range results.

A rough estimate of swath range can be made by considering the bottom reverberation to noise ratio from the long-range reverberation curves. From the data in Appendix A of [3], the swath range (one side) is estimated to 7 km.

It is uncertain whether the inversion method used here will work at long ranges, especially since the parameter μ is determined at short range before forward reflections from the bottom influence significantly the reverberation level. A way around this problem will be to store data when the sonar is operating in an area, and afterwards combine these data to produce inverted data for the whole area. An alternative approach is to attempt to resolve the ambiguities in long-range data by using information from multiple beams.

4.2 Estimation of scattering strength, reflection loss and transmission loss

Scattering strength and Reflection loss

Inversions of synthetic data indicated that it should be possible to measure scattering strength to an accuracy of ±2-3 dB from LFAS data. The objective function used for the inversions used only the first few seconds of data. Hence, the values for scattering strength are little influenced by reflection loss (propagation). For the long range, range dependent case it may be necessary to use a different objective function, which uses information from longer ranges.

It was found that the inversions for reflection loss were hampered by uncertainties in the forward modelling. Nevertheless, it should be possible to measure reflection coefficient by LFAS, but a pre-requisite is an improved understanding of the forward modelling.

But even if reflection loss is determined correctly, the inversion method is unable to resolve the individual parameters of the reflection loss model (sound speed and attenuation), due to strong parameter correlations. It may be necessary to determine these parameters from other measurements, such as echosounder.

Reflection loss and scattering strength may be wrong if propagation is wrong. But if the same model is used for inversion and prediction, the correct reverberation curve will result. However, extrapolation to different conditions (sea state, SSP, source/receiver depths) may give wrong results in such cases, as will the use of different models for inversion and prediction.

Decoupling the forward problem from scattering

An important question is whether the inversion method is able to decouple scattering and forward propagation. In other words, can we unambiguously determine scattering strength and reflection loss separately? It is shown in **[1]** that for a range-independent environment it is possible to separate these effects if departures from Lamberts scattering rule are small. However, in range-dependent environments it is difficult to uniquely decouple the forward problem from scattering. In such cases information about forward propagation is required in order to decouple the effects. The required information about forward propagation may be obtained in bistatic/multistatic operations.

Transmission loss and target strength

To obtain a correct estimate of transmission loss, it is necessary that the inversion method is able to decouple scattering and forward propagation, such that a correct estimate of reflection loss is obtained. This is discussed above.

Target echo level, and thereby probability of detection, cannot be determined correctly without a correct prediction of transmission loss.

4.3 Limitations due to sea state and sound speed profile

To produce reliable results the method requires a sufficient signal-to-noise ratio, SNR, or more specifically bottom reverberation to background (surface and volume reverberation and ambient noise) ratio. At high sea states surface reverberation masks bottom reverberation. The SNR achieved in a measurement depends, apart from sea state, on bottom type, SSP and array depth.

A sensitivity study was carried out for spring conditions (May) in Vestfjorden. The sound speed profile was upward refracting. The study showed that for clay bottoms the bottom reverberation was masked by surface reverberation when wind speed exceeds 2 m/s, while for sand bottoms surface dominates reverberation for wind speeds above 10 m/s [15]. However, these conclusions are not necessary applicable to other areas and oceanographic conditions. For the second sea trial, in the Norwegian trench in October, the SSP was downward refracting, causing less surface interaction, and probably lower sensitivity for wind speed.

The sensitivity to mismatch in sound speed profile was investigated in [6]. The study showed that reverberation is relatively insensitive to moderate range variations in sound speed.
The effect of departures from assumed SSP was also considered in [2] Sec 6.5.2. This study compared inversion results for the true SSP and an isovelocity profile. The isovelocity profile represents an extreme case for which no information about the sound speed profile is available. Results showed that some information about the SSP is required to obtain acceptable accuracy in the inverted parameters.

4.4 Constraints due to operational aspects

Time to cover an area

Time to cover an area depends on usable swath range, and whether anisotropy in bottom properties makes it necessary to cover the area along different headings. Swath range is difficult to predict in advance since it depends on many parameters (bottom type, SSP, sea state).

Calibration problem

Calibrated measurements are necessary to estimate scattering strength correctly. A calibration error will cause a corresponding error in the scattering strength parameter.
Calibrating the sonar includes source level, transmit and receive beam patterns, and a calibrated receiver including all processing gains in the system.

Impact on marine life

A worldwide concern is emerging about how high power low frequency sonar influence marine life, in particular marine mammals. When the sonar is operated, a procedure is followed to ensure that the interference with marine life is kept at an acceptable level. The procedure involves a sharp lookout for marine life during operations, and a ramp up of the sonar power after longer periods of no sonar transmissions.

Inversion would not require more source level than standard operations of LFAS. The sonar may also be operated at reduced power while still providing acceptable detection ranges. We used reduced power during the experiments compared to real sonar full power.

4.5 Comparison with other methods to collect bottom data

Current methods for estimating bottom properties involve *in situ* measurements (cores or grabs) and high frequency sonar. In principle, backscattering strength can also be obtained by direct measurements.

In situ methods are very time consuming, and as we have shown, they do not provide parameters that are useful for assessing the performance of LFAS systems.

Echosounders are more practical, but still provide data that may be unrepresentative for a long-range low frequency system because they measure only local properties at normal incidence, and usually at a higher frequency than that of interest.

Traditional direct measurements of backscattering strength involve a simple geometry with a single surface interaction. Such measurements are restricted to high frequencies or deep water. When the water depth becomes too small, a long array is required to separate arrivals. In shallow water a direct measurement becomes unfeasible due to the need to deploy a long array.

For REA applications, it seems that the only practical method to collect some bottom data for updating bottom databases is through reverberation inversion. Such a measurement provides the potential for long-range coverage from a single platform, precisely at the frequencies and grazing angles of interest to the sonar.

4.6 Extending the results

An important question is whether it is possible to extend the results of RUMBLE to other conditions and systems. In other words, can we extrapolate the results obtained in an area to (i) a different sea state (ii) a different SSP or (iii) other frequencies and angles, i.e. other systems?

The ability to extrapolate depends on several factors: (i) does the inversion produce ‘equivalent’ or true bottom parameters and (ii) does the bottom model allow extrapolation. First, inversion may produce an equivalent model, i.e., a set of parameters that gives good match to the measured reverberation data, but which does not represent the true geophysics. Such unphysical bottoms may result when forward propagation and scattering could not be decoupled unambiguously, but may also results from ambiguities inherent in the inversion method itself.

Second, bottom scatter models may be empirical or physics based. A physics based bottom model allows (at least in principle) extrapolation to unmeasured frequencies, angles and bottom types while an empirical model does not. Extrapolation should only be performed when the inversion produces true, physical bottom parameters.

Somewhat related is the question of whether different reverberation models could be used for inversion and prediction. At present, it seems that different reverberation models sometimes produce inconsistent results. We therefore recommend using the same model for both applications.

4.7 Relative importance of bottom type and bottom topography for reverberation prediction

An important question is whether the biggest improvements in prediction capability come from a better knowledge of bottom type or bottom topography. The answer to this question tells us where it is worth to put the most effort: on refining the inversion method or to measure water depth more accurately.

The simulations made with VENUS and LYBIN are not sufficient to answer this question. A problem is that the effects are coupled. However, it should be possible to examine separately the effect of modelling with (i) improved bathymetry and (ii) with improved bottom data only.

4.8 Real or effective geo-acoustic parameters

In all inversions there arise ambiguities whereby a measurement can be explained equally well by different combinations of parameters. Reverberation inversion is hampered with more ambiguities than conventional MFI. Due to ambiguities, the inversion method is likely to produce effective acoustic parameters, and not the true geophysics.

There are several possible ways to resolve such ambiguities: One approach is to supplement the reverberation measurements with a local measurement of bottom properties using echosounder. Another approach is to determine bottom parameters from short-range matched field inversions, utilising the horizontal distance between source and receiver array. It may also be possible to resolve such ambiguities by exploiting multiple looks at the same patch from different distances.

4.9 The potential of the echosounder

The role of the echosounder for the RUMBLE experiments was to provide independent information to check the validity of the acoustic inversion. However, the echosounder provided valuable information, complementary to the information from inversion of LFAS data, which could be utilized in a final measurement system. A combination of measurements that would provide all the necessary information for a range-independent environment would be: water depth, sediment sound speed and density from an echosounder, plus scattering strength and attenuation from LFAS.

Possible disadvantages of using echosounder data are that (i) inconsistencies may arise in merging data from two different sources, especially when the measurement is an indirect one, and (ii) a calibrated echosounder system is required.

4.10 Areas of improvements

It was found that inversion for reflection loss was hampered by uncertainty in the forward modelling. When two different reverberation models were employed for the same problem, with the same bottom model, they produced different results. The inconsistencies between the models come as a result of different algorithms and approximations used by the models. There is a trade off between accuracy and speed, and we need a fast model to carry out inversion.

The performance of more complex sub-models for scattering and reflection loss, preferably physical based, should be investigated. At present a very simple scattering model (Lamberts rule) is used. The advantage of more complex sub-models is that they better represent actual physical mechanisms; the disadvantage is the larger number of parameters.

The azimuth dependence of scattering strength may be included in the final maps.

Multiple looks (directions and ranges) and beams other than broadside may be utilized to obtain better data coverage.

Evaluating the uncertainty in the inferred seabed properties may provide valuable information.

Transmission loss is difficult to determine accurately in a range dependent environment by inversion of reverberation data. The problem may be resolved by determining forward propagation (bottom reflection loss) from a short range measurement. In bistatic/multistatic operations transmission loss could be measured by the receive ship.

Exploiting echosounder information may give better system performance. The echosounder provided valuable information, complementary to the information from inversion of LFAS data, which could be utilized in a final measurement system, as discussed in paragraph 4.8

It was considered necessary to gain experience with the method for the range-independent case before moving on to general range-dependent environments. The model developed for the project handles range-dependent bathymetry but not SSP. However, introducing range dependent bottom properties present quite a challenge to the inversion method since the number of search parameters (dimension of minimization problem) increases significantly. At present one average value is determined for the entire range. The effects of variable bathymetry and bottom properties are therefore ‘absorbed’ by effective values of the inverted parameters.

5 CONCLUSION

The inversion method

Bottom databases are often inadequate in shallow water resulting in unreliable sonar performance predictions. The aim of RUMBLE is to investigate the potential of using existing LFAS sonars to measure "through-the-sensor" the seabed characteristics affecting long-range acoustic propagation.

The method uses a matched beam inversion technique to estimate bottom parameters from the reverberation received by the ships own sonar.

Potential advantages of the method are that it allows a rapid characterisation of an area, precisely at the frequencies and incidence angles of interest to the sonar.

The accuracy of the method and its robustness to mismatch has been studied using synthetic reverberation data: It was found that scattering strength could be determined to an accuracy of ±2-3 dB.

Inversion for reflection loss is hampered by uncertainty in the forward modelling. The method is tolerant to small errors in water depth, sonar depth, wind speed and sediment sound speed profile.

The inversion method is likely to produce effective acoustic parameters, and not the true geophysics. There are several possible ways to resolve such ambiguities: One approach is to determine bottom parameters from short-range matched field inversions, utilising the horizontal distance between source and receiver array. Another way of resolving such ambiguities is by exploiting multiple looks at the same patch from different distances.

Data processed

Two sea trials were conducted, providing data for the assessment of the method. A simple area (Vestfjorden) and a more complex area (Norwegian trench) were selected for the measurements.

The data used for the inversion (second sea trial) were the broadside beam reverberation from the long (100 ms) CW pulse. The short CW data were not processed because of the need for a bistatic model, which was not available. Data from the high energy HFM pulse has not been processed. It was considered necessary to gain experience with the method for the range-independent case before moving on to general range-dependent environments.

Results from inversion of reverberation measurements

The final results of RUMBLE are local models for bottom backscattering and bottom reflection loss, as well as (geographic) maps of the parameters of these models. The particular local models selected were the Lambert rule for backscattering and the Rayleigh coefficient for reflection loss. Scattering strength is therefore characterized by a single parameter μ (the Lambert constant), while the bottom reflection loss depends on three parameters (c, α, ρ).

Significant changes in μ, up to 15 dB, were found across the survey area.

Inverted values for sediment sound speed and attenuation were consistently higher than expected for these parameters. The combination of these parameters, however, gives plausible values of bottom reflection loss.

Azimuthal anisotropy in scattering strength, up to 4 dB, was found in the area. Scattering strength was higher looking in the E-W direction than in the N-S direction. This observation is consistent with the presence of iceberg scouring in the area, with a general orientation in the N-S direction.

Measurements of scattering strength were reproducible for repeated legs over the same area (in different wind conditions).

There is a limitation due to sea state. The maximum sea state in which successful inversions could be performed depends on bottom type (softer bottoms require lower winds), SSP and sonar depth.

Echosounder data

Grain size inferred from echosounder was consistent with grab samples.

Echosounder provides a means to extend seabed information obtained from grab samples, to obtain a much greater coverage than grab samples on their own.

The bottom properties measured by the echosounder were shown to be representative of the top few cm of the sediment.

It seems possible to infer sediment sound speed and density appropriate for the low frequency band of LFAS from echosounder data. The procedure adopted automatically allows for vertical gradients in sound speed and density in the sediment, assuming that the grain size does not change with depth.

Compressional wave attenuation of the sediment could not be measured by the echosounder.

No information from the echosounder was used for the LFAS inversions. The main reason for not using echosounder data was that it would then lose its value as ground truth. But the echosounder might provide valuable data that could be an integral part of a final measurement system.

Consistency with ground truth

LFAS scattering strength μ showed no apparent correlation with grain size, indicating that the properties of the top few cm of the sediment are a poor indicator of low frequency scattering strength.

The correlation between echosounder reflection coefficient (b/π) and LFAS reflection loss is weak. A correlation between surface sediment type or grain size (as measured by echosounder reflection coefficient) and low frequency reflection loss was expected. The reason such correlations have been observed to little extent could be that we are unable to measure the parameter b with sufficient precision.

What can/cannot be measured by LFAS

It was demonstrated that scattering strength μ could be measured by LFAS.

Inversion for reflection loss is hampered by uncertainty in the forward modelling. Reflection loss at low frequency and grazing incidence can, in principle, be measured by inversion of LFAS data, but a prerequisite is an improved understanding of the forward modelling.

The method is not able to resolve the individual parameters of the reflection loss model (sound speed and attenuation).

It was shown that in the range independent case scattering and reflection could be separated, which means that transmission loss can be determined accurately in this case.

In general, for range-dependent environments, it is difficult to uniquely decouple the forward problem from scattering, and it may be necessary to measure the forward propagation (TL) separately in order to separate scattering strength from reflection loss. This could be achieved in multistatic operations.

Expected improvement

The expected improvement of the RUMBLE method over predictions using standard databases and scattering index models was estimated to:

- About 10 dB when bottom type was determined from previous propagation measurements in the area.
- Up to 20 dB when bottom type was determined from grab samples or charts

Hence, the improvements achieved depend on our previous knowledge of the area. But even in a well-known area there is a gain in using the RUMBLE bottom model.

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