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RUMBLE FINAL REPORT (DE 19)

JENSERUD Trond, KNUDSEN Tor

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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 present report presents an overall assessment of the work and provides the main conclusions.

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1 INTRODUCTION

In shallow water areas there is a shortfall in the capability to predict active sonar performance. An idea has emerged to use operational Low Frequency Active Sonars to measure “through-the-sensor” the seabed characteristics affecting long-range acoustic propagation in shallow water. The results from such measurements could be used both to optimise sonar system settings in real-time, and to update bottom databases to enhance the quality of sonar performance predictions.

Project RUMBLE (BOTTOM ROUGHNESS MEASUREMENT BY USE OF LOW FREQUENCY SONAR) is concerned with investigating the potential of such a concept. The work has consisted in developing a method for measuring bottom properties from the reverberation received by an operational LFAS, and in evaluating the method on real data from two sea trials.

This report is deliverable DE19 of the RUMBLE project. The scope of the report is to provide an overall assessment of the method, and to give the main conclusions of the work.

The report is structured as follows: Sec. 2 and 3 provides some background for the work, and state the aims of the project. Sec 4 gives a brief summary of the work carried out. Advantages and drawbacks of the method, mainly from an operational point of view, are discussed in Sec. 5. Finally, Sec. 6 presents the main conclusions.

A complete list of reports produced by the project is included.

2 AIMS AND OBJECTIVES

The aims of project RUMBLE have been:

- To enhance our capability to predict active sonar detection ranges in shallow water.
- To assess the capability of an operational surface ship Low Frequency Active Sonar (LFAS) to measure the bottom environmental parameters necessary to predict bottom reverberation

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 ships own (LFAS) sonar. The advantages of using own sonar to measure bottom properties include: (i) rapid assessment of bottom properties, (ii) bottom parameters are measured at frequency of interest for operational sonar and (iii) the possibility of 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 loss, from the reverberation returns of the ships own sonar.

The objectives defined for achieving these aims have been:

- To develop a reverberation inversion method
- To carry out measurements to provide data for testing and validating the method

3 BACKGROUND

Shortfall in current ASW capabilities in shallow water

For ASW operations in shallow water there is a critical shortfall in the capability to reliably predict active sonar detection ranges. The lack of predictive skill comes mainly from inadequate knowledge about the environment, but may also be due to inadequate modelling capability.

Limitations for LFAS

For Low Frequency Active Sonar (LFAS), the main environmental influences are water depth and bottom profile, bottom characteristics, sound speed profile and sea surface characteristics. Furthermore, the scattering of acoustic energy from the sea surface and the seafloor is very important for understanding both propagation and reverberation, particularly in shallow water environments. Forward scattering (reflection loss) plays a major role in determining propagation, and backscattering is particularly important for active sonar systems, as it determines the background signal against which target detections must be made. Reverberation, mainly due to bottom features, causes false alarms, and is often the factor limiting active sonar detection ranges in shallow water.

Surface reverberation is caused by scattering from waves and bubbles. The distribution of waves and bubble layers can be estimated from wind speed or sea-state. Hence, surface reverberation can be estimated quite well from accessible parameters such as wind speed. This is unfortunately not the situation for bottom reverberation, where the parameters required for describing the reverberation are difficult to achieve. Bottom reverberation is caused by scattering from the roughness of the sea floor. But it may also be necessary to take into account “invisible” roughness such as variations of surface impedance and deeper layers, as well as inhomogeneities within the sediment volume. These parameters are very difficult to measure with the required spatial resolution. The distribution of sediments may also vary considerably geographically as well as vertically within an area.

Method

As it is unrealistic to expect that sufficiently detailed sonar databases will exist for all areas of interest, the capability to quickly assess the sonar-operating environment just prior to, or during deployment becomes important. We therefore need a method for rapid assessment of the bottom parameters that are required for producing reliable predictions of active sonar detection ranges. Current methods for estimating bottom properties, such as sediment cores and high frequency sonar, are very time consuming and measure sediment properties at a higher frequency than that of interest. Obtaining relevant bottom parameters for large areas can probably only be achieved through inverse modelling.

Military relevance

With increasing emphasis on shallow water operations there is a requirement to develop tactical advice to exploit these environments for naval operations such as ASW, MW, MCM amphibious operations and special force operations. For ASW operations, the principal threat is the conventional submarine, for which detection and localization are becoming increasingly difficult. To maximize the military effectiveness of Low Frequency Active Sonar (LFAS), the impact of the shallow water environment must be better understood and particularly the limitation in target detection due to reverberation.

4 WORK CARRIED OUT

The work has included the development of an 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. The work was divided into six work packages as follows:

- WP1: Acoustic modelling
- WP2: Inversion methods
- WP3: Sea trials
- WP4: Data analysis
- WP5: Operational assessment
- WP6: Management

The work is reported in a number of RUMBLE reports. A complete list is included in the references.

Acoustic modelling

A 3D global reverberation model TAMAR (Towed Array Model of Acoustic Reverberation) has been developed [5]. The model predicts reverberation power versus time after beam-forming and matched filter processing. The beamformer has the capability to discriminate between port and starboard sides of the towed array. TAMAR is a ray model, and handles weakly range dependent environments. The model includes local models for scattering and reflection from the sea surface and ocean bottom.

Local bottom scattering models with several levels of complexity are provided [4]. The models range from simple phenomenological to complex, physics based models.

Inversion methods

The objective of the RUMBLE project is to determine seabed properties, by inversion of the reverberation field measured by the operational sonar. A survey of geoacoustic inversion methods was carried out and a geoacoustic inversion technique, using the reverberation field received on the CAPTAS array, has been developed [1]. The method is a matched beam inversion technique using the Genetic algorithm as global optimisation method, and the reverberation model TAMAR as the forward model.

The properties of the reverberation inversion method have been investigated through a study of synthetic reverberation data. It was shown that geoacoustic inversion on reverberation data presents particular problems compared to conventional matched field inversion on forward propagation data.

Another important use of studies on synthetic data is to provide guidance on deployment configuration, such as sonar depth and pulse type, in order to optimise the sensitivity for bottom parameters. A sensitivity study was performed for first sea trial in Vestfjorden [15]. The study assessed under which conditions (sea state, bottom type, measurement configuration) successful inversion of bottom parameters could be achieved.

Sea trials

During project RUMBLE two sea trials have been conducted, the first in Vestfjorden in May 2001, and the second in the Norwegian Trench south of Bergen in September-October 2002. The purpose of the sea trials was to provide the experimental data necessary in order to validate the method for estimating bottom properties. The sea trials included measurements of reverberation from different bottom types and under different conditions, as well as ground truth and the environmental data required for the subsequent analysis. Bottom types ranged from simple, homogeneous, flat bottoms (Vestfjorden) to more complex, range dependent bottoms (Norwegian Trench), presenting more challenges to the method.

The planning and execution of the sea trials are described in [8], [9], [10]and [11].

Data analysis and assessment of inversion results

The performance of the inversion method has been evaluated using data collected during the two sea trials.

The analysis of the reverberation data included beamforming (with left-right discrimination) and conditioning of data prior to the inversion for bottom parameters. In the inversions a simple, range independent bottom model was assumed. The output of the inversion process is a set of parameters describing the scattering strength and reflection loss of the bottom.

Ground truth consisted of grab samples and echosounder data, and was analysed to provide independent estimates of bottom parameters. Finally, the performance of the inversion method was assessed by a comparison with ground truth.

Due to interference problems with other acoustic instruments in the first sea trial, causing reduced data quality, it was decided to concentrate the remaining efforts on the second sea trial.

The analysis of the first sea trial (Vestfjorden) is reported in [2], and the analysis of the second sea trial (Norwegian trench) is reported in [3].

5 GLOBAL ASSESSMENT

5.1 Advantages/drawbacks of the method

5.1.1 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 the full source level, 209 dB re 1 μPa @ 1m, was used. 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. For the second sea trial a reduced source level, 205.5 dB re 1 μPa @ 1m, was used.

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 maximum swath range that can be obtained by an operational system has not been established because priority was put on short range inversion (the high-energy HFM transmissions have not been analysed), and also because our experimental equipment produced significantly lower source level than a real active low frequency sonar.

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 as 7 km.

It is uncertain whether the inversion method used here will work at long ranges, especially since the backscattering 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.

5.1.2 Possibility to collect data during exercises or transits

The requirements for reverberation measurements are that (i) a particular signal is transmitted, (ii) the tow depth should be optimised for bottom interaction, and (iii) there may be a speed restriction to avoid noise.

These requirements should not interfere too much with normal operations of the sonar, although the optimum depth for submarine detection may not be the best for reverberation measurements. The signals transmitted for reverberation measurements should not reduce the capability of the sonar to detect submarines: The signal used for detecting submarines can probably be utilized for measuring bottom parameters at long ranges. A separate short signal can be transmitted at regular intervals for measuring bottom parameters at short ranges.

In transits there will be a speed restriction in order to obtain data of good quality. There is no impact during a search because this would also require a low speed.

5.1.3 Possibility to use results in real time for calibration of sonar POD (Performance Of the Day)

The requirements for carrying out this task are that good estimates of forward propagation (transmission loss) and reverberation level could be provided in real time.

The final system should be able to provide predictions in near real-time. However, the inversion method may be unable to provide accurate estimates of reflection loss (and thereby transmission loss) in range-dependent environments. The reason is that scattering and reflection could not be unambiguously decoupled in the range-dependent case. The required information about forward propagation may be obtained in bistatic/multistatic operations.

5.1.4 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, fish density, 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.

5.1.5 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 even be operated at reduced power while still providing acceptable swath ranges. We used reduced power during the experiments compared to real sonar full power.

5.1.6 Comparison with other methods to collect bottom data

Current methods for estimating bottom properties incude *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. Nevertheless, echosounder measurements can be converted to equivalent low frequency data if the sediment grain size is assumed uniform with depth.

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 vertical array.

For REA applications, it seems that the only practical method to collect 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.

5.1.7 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: Does the inversion produce ‘equivalent’ or true bottom parameters, and 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, at least until these inconsistencies are resolved.

5.2 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.

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.

6 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.

Inversions were carried out for the measured broadside beam reverberation from the 10 ms CW pulse for Vestfjorden, and the 100 ms CW pulse for the Norwegian Trench. Data from the high-energy HFM pulse has not been analysed. It was considered necessary to gain experience with the method for the range-independent case before moving on to general range-dependent environments. Due to interference problems in the first sea trial, causing reduced data quality, efforts were concentrated on the second sea trial.

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 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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