A Geoacoustic Inversion Method for Range-Dependent Environments using a Towed Array

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Abstract–**Seabed properties are determined using a matched field geoacoustic inversion approach with towed, horizontal array data. Towed acoustic systems are advantageous because they are easy to deploy from a ship and the moving platform offers the possibility for estimating spatially variable(range-dependent) seabed properties. In this paper inversion results using measured, towed array data will be presented. Simultaneously collected vertical array array data was also inverted and those results will be used for comparison.**

I. Introduction

Acoustic propagation in the oceans shallow waters is influenced by several environmental factors including surface wave-height conditions, water column sound speed properties, bathymetry and seabed type. The seabed often has the strongest effect on propagation and its properties are probably the most difficult to obtain. Differences in seabed properties can greatly influence the performance of active and passive sonar systems. To estimate sonar systems performance, sound propagation prediction tools are used and these all require, as input, the geoacoustic properties of the seabed. Existing archives containing values for the seabed characteristics are generally not known with sufficient accuracy and detail for these modeling purposes. Techniques that can be implemented easily are needed to characterize the properties of the seabed.

Matched field processing (MFP), geoacoustic inversion is a technique that has shown success in characterizing the seabed for the most important parameters for propagation prediction. This remote sensing, inverse method uses down-range acoustic measurements to infer properties of the seabed. Computer simulations model down-range acoustic responses to different seabed types, and efficient search algorithms are applied to find the environment giving an optimal match between modeled and measured data [1–5]. MFP inversion has been demonstrated experimentally, but except for [6, 7] these were based on vertical line array (VLA) data. The VLA configuration is sensible as, ideally, the propagating acoustic field is received at all angles. However, as the range increases between source and receiver, variability in the environment can destroy the prediction capability of the matched field processor due to inaccuracies in the modeling. This variability can be caused by, among other factors, changes in seabed properties, bathymetry or ocean sound speed. As it is *a priori* imperfectly known, this range-dependence is difficult to include in the numerical modeling required for the MFP inversion. Additionally, with either the source or array in a fixed location, the inverted bottom properties are averaged over the distance between the two. This is problematic in cases where range-dependent seabed properties exist. In these cases, averaged seabed properties may not correctly capture the behavior of the field (i.e. when used for modeling this can lead to wrong field predictions).

Using a towed horizontal line array (HLA) for MFP inversion, several practical and modeling difficulties associated with VLA inversions can be overcome. (1) Towed arrays are easy to deploy from a ship and are widely available. (2) The requirement for range-dependent modeling in the MFP inversion is eliminated because the seabed and bathymetry can usually be assumed constant over the short distance separating source and HLA. (3) Similarly, since HLA and sound source are kept at short-range separation, MFP degradation due to water column, sound speed variability is minimized or eliminated. (4) A towed system is advantageous because range-dependent properties can be estimated without requiring range-dependent MFP inversion.

To test the possibility of determining seabed properties using a towed source and array the MAPEX2000 series of experiments were conducted in the Mediterranean Sea. The first demonstration of the concept of MFP geoacoustic inversion using horizontal arrays is documented in articles by Jesus and Caiti [6] and Caiti, Jesus and Kristensen [7]. The MAPEX2000 experiments extended these concepts by using broad-band signals for inversion and collecting simultaneous data on a moored VLA. Both HLA and VLA broad-band data sets were used for MFP geoacoustic inversion. The purpose of the experiments was to validate the HLA inversion method and compare results with those using VLA data. Details of the experiment are described in Section III and [8].

II. The Inversion method

The geoacoustic inversion method has several components. (1) The experimental configuration, (2) the forward propagation model, (3) the assumed geoacoustic model for the site, (4) the cost function, (5) the search algorithm and (6) an a post-inversion estimate of the quality of the results and errors. These components are briefly described below.

(1) Determining the ideal experimental geometry for a towed

array inversion experiment requires sensitivity studies to compare various geometries and signal types. And, it is difficult to determine this using simulations since many of the errors and uncertainties found experimentally are difficult to duplicate in simulation. These issues are complicated and will be considered in future work. But, for the experiment described in Section III, the towed array was kept as deep as possible, this was to measure acoustic energy that interacted with the seabed at or near the critical angle. It is also expected that broad-band signals will contain more information than single-tones [9] and for that reason, signals covering the band 220-800 Hz were used for the inversion work.

(2) The propagation model should be chosen so it is suitable for the experimental conditions. For the HLA configuration considered here, the acoustic source is only a few hundred meters from the hydrophones and steep angle propagation paths cannot be neglected. Therefore, the model must be valid in the near-field so the broad-band, complex normal mode model ORCA [10] was used. This is a layered normal mode model that includes the continuous spectrum. Other models may be appropriate, including ray tracers that correctly treat the seabed interactions.

(3) The geoacoustic model is the underlying assumption about the make-up of the seabed which can be implemented using a set of input parameters to the propagation model. Only parameters which influence the down-range acoustic field should be considered. Otherwise, there is little hope that the acoustic fields will contain enough information to invert for those parameter values. Typically, a simplified description of the seabed is required to produce a stable inversion as having too many parameters (and parameter coupling) may cause an apparent instability [11]. Here, a one-layer model consisting of a sediment layer over-lying an infinite half-space is considered. The parameterization and search space for both the seabed and experimental geometry (i.e. source and receiver positions) must be considered carefully to allow finding the best solution but not to overburden the search algorithm. The search parameters and search bounds for the geoacoustic parameters are given in Table 1 and for the geometrical parameters in Table 2.

Table 1. Seabed parameter labels and minimum and maximum values in the search space. Attenuation and density are constant through the sediment and sub-bottom. Sound speeds refer to compressional acoustic waves and attenuation is given in units of decibels per wavelength.

Parameter	**Minimum**	**Maximum**
Sed. thickness: h_{sed} (m)	0.1	20
Sed. speed: c_{sed} (m/s)	1450	1700
Attenuation: α (dB/λ)	0.0	1.0
Density: ρ (g/cm^3)	1.0	2.5
Sub-bot. speed: c_{bot} (m/s)	c_{sed}	$c_{\text{sed}} + 250$

(4) The cost function quantifies the agreement between the experimental measurements and the modeled data. Two cost functions are used here. The first correlates the modeled and measured pressure fields over the array of hydrophones and the magnitudes are summed over frequency as shown in (1):

Table 2. Geometric parameters and search intervals (around estimated values).

Parameter	**Search** interval
Source range	± 5 m
Source depth	± 1 m
Array depth	± 1 m
Array tilt	± 1 m
Bottom depth	± 1 m

$$B_H = \frac{1}{N_{\text{F}}} \sum_{j=1}^{N_{\text{F}}} \frac{|\sum_{i=1}^{N_{\text{H}}} p_{ij} q_{ij}^*|^2}{\sum_{i=1}^{N_{\text{H}}} |p_{ij}|^2 \sum_{i=1}^{N_{\text{H}}} |q_{ij}|^2}. \quad (1)$$

The second cost function is given by (2) and it correlates the acoustic field in frequency with the magnitudes summed over the hydrophone array,

$$B_F = \frac{1}{N_{\text{H}}} \sum_{i=1}^{N_{\text{H}}} \frac{|\sum_{j=1}^{N_{\text{F}}} p_{ij} q_{ij}^*|^2}{\sum_{j=1}^{N_{\text{F}}} |p_{ij}|^2 \sum_{j=1,}^{N_{\text{F}}} |q_{ij}|^2}. \quad (2)$$

In (1) and (2), N_{F} is the number of frequency components, N_{H} is the number of hydrophones and the measured and modeled complex pressure vectors are p_i and q_i (* denotes the complex conjugate operation). Both correlators take on a value of 1 for two identical signals and 0 for completely un-correlated signals (the actual cost function is $1 - B_H$ and $1 - B_F$). Equation (1) performed better on the VLA and (2) better on the HLA. The reason for this is not completely known at this time, but it may be because the transmitted signal was better equalized to produce a flat spectrum than the equalization to produce a flat hydrophone response across the HLA. That is, the hydrophone response was better equalized across the VLA than for the HLA. For the inversions considered in this paper, (1) is used with the VLA data and (2) with the HLA data.

(5) The search space for these inversions is enormous and the cost function typically has many local minima which necessitate using global search methods such as a genetic algorithm or simulated annealing. These are useful to find the optimum set of parameters corresponding to the true minimum of the cost function [2, 3]. The inversions in this paper use a genetic algorithm in the SAGA inversion package [12]. The basic principle of a genetic algorithm is as follows: First, an initial population is created randomly; the first generation. Out of the initial population, the most fit members (i.e. those with the lowest cost function value) have the highest probability to be selected as "parents". From the parents, "children" are obtained by the operations of crossover and mutation. The crossover operation can duplicate one of the parent's parameters or perform a bit crossover of the two parents. That is, using bit string representations of the parameter values, form the child's string by taking part from one parent and part from the other. The mutation operation makes a change of a single bit in the parameter

value string to allow the search to escape local minima. Part of the children are then used to replace the least fit members of the initial population creating the next generation. Successive generations become increasingly fit and the process is continued until the optimization process has converged. For the inversions in this paper, a total of 40,000 forward model computations (or 40,000 individuals) are used in the genetic algorithm search.

(6) Inversion errors can be difficult to assess due to the difficulty in establishing "ground-truth" values for the geoacoustic parameters. Several possibilities exist for estimating the accuracy of the inverted solution. A simple approach is to plot the correlation value (from either (1) or (2)) versus corresponding parameter value. In this way, the distribution of good correlation values should cluster near the true parameter value. The character of such plots give an indication of the sensitivity of each parameter although this is biased somewhat because only the parameter combinations in the search are considered. This bias should not be too large if many forward model (possible parameter sets) are considered (40,000 for the data considered here). Details about the ways to obtain estimates of the *a posteriori* probability densities for each parameter can be found in [13]

III. The MAPEX2000 Experiments

The MAPEX2000 series of experiments were conducted by the SACLANT Undersea Research Centre and took place on the Malta Plateau (between Italy and Malta) from February 22 to March 27, 2000. The purpose of the experiments is to validate the HLA geoacoustic inversion method and compare this with a VLA geoacoustic inversion. The setup included a moored, vertical array and a towed source and towed horizontal array. The experimental configuration is shown in Fig. 1. Here, measurements are taken from the March 7, 2000 experiment.

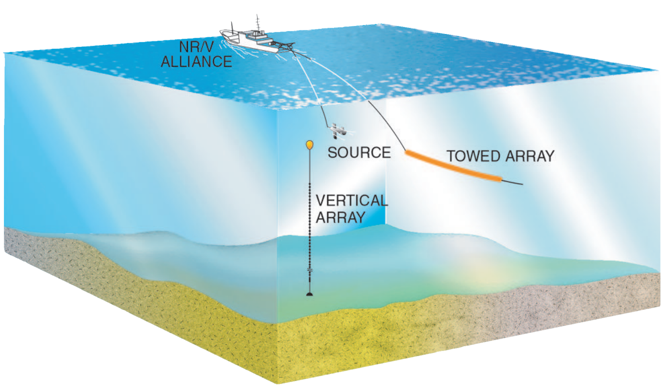

Fig. 1. Experimental geometry for March 7, 2000.

A. Acoustic data

The March 7, 2000 experiment included broad-band acoustic signal transmissions using two flextensional sources mounted in a tow fish. A sequence consisting of 1 second linear frequency modulated (LFM) sweeps from 150–800 Hz were repeated every minute (in addition to other signal transmissions not included in this paper). All transmissions were equalized using a programmable signal generator to produce signals having a flat spectrum. The received time series was converted to the frequency domain using a Fast Fourier Transform. Frequency bins corresponding to 220–800 Hz in 10 Hz increments were used in the inversion for comparison with modeled results.

The HLA is 254 m in total length and for data considered here, the entire length of the array is used (128 hydrophones spaced at 2 m). Both the array and source were towed from the NRV *Alliance* at approximately 5 knots. The distance between the sound source and the closest hydrophone on the HLA was about 300 m. The tow depths of the source and HLA varied slightly during the acoustic runs, but generally were maintained at 55–65 m depth. The VLA was deployed in 130 m depth water at position $36°26.668'$ N and $14°46.751'$ E and the acoustic data were received on NRV *Alliance* by radio telemetry. The VLA has 48 equally spaced hydrophones covering 94 m of the water column (spanning depths of 24–118 m). The VLA was bottom moored and kept upright using a sub-surface float.

B. Oceanographic data

Sound speed profiles were measured at various times before, during and after the acoustic experiments. When possible, conductivity, temperature and depth (CTD) measurements were taken from NRV *Alliance* (usually before and after each towed source acoustic run). During the acoustic runs, expendable bathythermograph (XBT) probes were deployed from NRV *Alliance* to measure the ocean temperature profile. The salinity from the CTD casts were used to calculate sound speed from the XBT probes. Typical sound speeds taken from two XBT probes on March 7, 2000 are shown in Fig. 2. The profiles are slightly upward refracting (the typical condition for the experimental area in March) but the overall change in sound speed over depth is only about 4 m/s. For the geoacoustic inversions considered here, the input sound speed profile for the acoustic modeling was taken from the XBT data closest in time to the acoustic transmission.

IV. Inversion results

At 09:07 UTC a 1-second sweep was transmitted from *Alliance* located at $36°26.688'$ N and $14°46.230'$ E (denoted ping-9:07). This sweep was simultaneously recorded on the HLA and the VLA (the VLA was about 1 km from the source). The same ping was inverted from receptions on the HLA and VLA using the search procedure and search intervals that were outlined in Section II (see Tables 1 and 2). Equation (2) was used as the correlation function for the HLA inversions and (1) for the VLA.

Associated with each forward model computation is one set of parameter values and a correlation value giving the quality of fit between data and model. If, for each parameter, the correlation values were plotted against the parameter values there would be a scatter plot of dots with a single dot for each forward model computation. In some cases the dots may land near or on the same point as another dot (if it produces a good

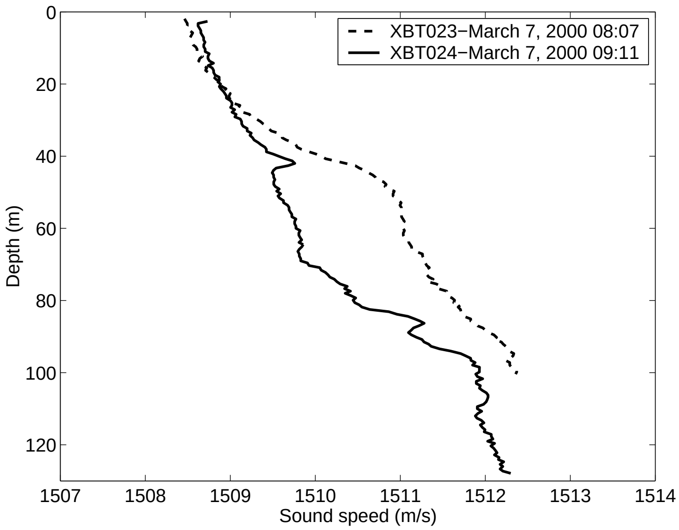

Fig. 2. Sound speed taken from XBT casts at positions $36°32.45'$ N and $14°49.20'$ E (at 8:07 UTC) $36°27.34'$ N and $14°46.47'$ E (at 9:11 UTC) on March 7, 2000.

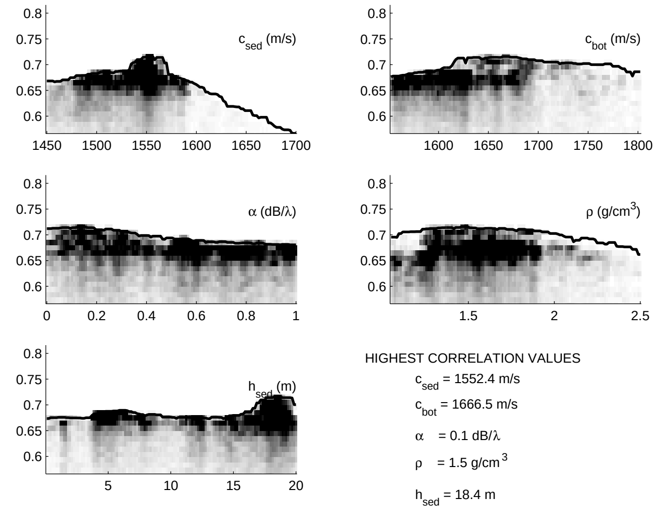

Fig. 3. MAPEX2000 HLA measured data inversion using propagation model ORCA from ping-9:07 on March 7, 2000. Correlation values (y-axis) are plotted against parameter value (x-axis) for each of 40,000 forward models included in the genetic algorithm search. A single dot is placed in each panel corresponding to the correlation and parameter value for that particular forward model computation. The darker areas indicated where the search algorithm sampled the parameter more heavily.

correlation, the search algorithm may want to return to that particular parameter value). These dots can be put on a single plot with a gray scale which indicates darker areas for places where the parameter value is heavily sampled. If a parameter is well determined, there should be a peak in this type of plot near the true value for that parameter, and, the area around the peak should be more heavily sampled than the areas that don't fit the data well. In addition, there is a single set of parameters that corresponds to the model that produced the overall best fit to the data (highest correlation over the all forward model computations). For a well determined problem, the best fit parameter values should be near the peak in each of the scatter plots. This type of scatter plot is shown in Fig. 3 for the HLA inversion and in Fig. 4 for the VLA. For both HLA and VLA inversions, 40,000 forward model computations were performed using the ORCA propagation code.

Both the HLA and VLA show clustering of the high correlation values near the best-fit solution. The best-fit seabed parameters are given in the lower right hand corner of Figs. 3 and 4. Also, both the HLA and VLA agree with each other in the values for each of the seabed parameters (e.g seabed sound speed and layer thickness).

A. Geoacoustic inversion over a range-dependent seabed

The advantages of using a towed array-towed sound source configuration becomes more obvious in range-dependent areas. For a fixed, VLA like that used in MAPEX2000, only the sound source is mobile to probe the range-dependent environment. However, a VLA, MFP inversion introduces modeling problems since the range-dependence needs to be included. The HLA configuration avoids (or at least minimizes) this difficulty as the distance between source and receiver is kept small (on the order of a few hundred meters) and range-dependence can be neglected. A second inversion was carried out for a ping taken at 08:05 UTC from *Alliance* located at $36°32.580'$ N and $14°49.260'$ E (denoted ping-8:05). The water depth at the source-HLA location was 99 m and the VLA was still in the same position as for ping-9:07 (in water depth of 130 m). Doing a VLA inversion for ping-8:05 is problematic due only to the bathymetry change of 31 m between the source and VLA locations. Also, there is about 11 km between source and VLA and range dependent ocean sound speeds may need to be included. Further, the bottom properties also change along the track between ping-9:07 and ping-8:05. The area near ping-8:05 is characterized by a very soft layer on top of a harder sub-bottom. The HLA, seabed inversion results are shown in Fig. 5. Again, the search had 40,000 forward model computations that were performed using ORCA and the search intervals were those given in Tables 1 and 2. The different bottom type near ping-8:05 is evident from the results in Fig. 5. The soft layer is detected and is about 10 m in thickness. The lower sub-bottom speed is also well determined which is likely because the soft sediment layer allows better acoustic penetration down to the sub-bottom. A VLA inversion was attempted using a range-independent assumption even though the water depth changed along the track by about 31 m. The VLA results showed a very poor correlation for the best-fit solution and none of the geoacoustic parameters were well determined. It is possible that including the range dependent bathymetry would improve the best-fit correlation however, it would remain difficult to interpret the averaged seabed properties found over the 11 km track.

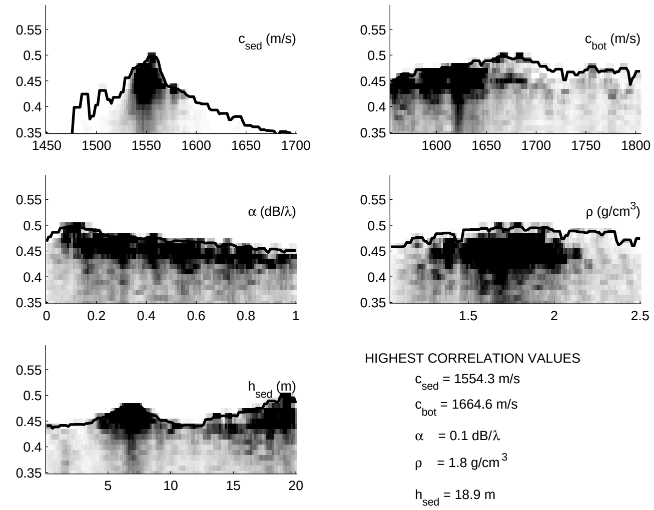

Fig. 4. MAPEX2000 VLA measured data inversion using propagation model ORCA from ping-9:07 on March 7, 2000. Correlation values (y-axis) are plotted against parameter value (x-axis) for each of 40,000 forward models included in the genetic algorithm search. A single dot is placed in each panel corresponding to the correlation and parameter value for that particular forward model computation. The darker areas indicated where the search algorithm sampled the parameter more heavily.

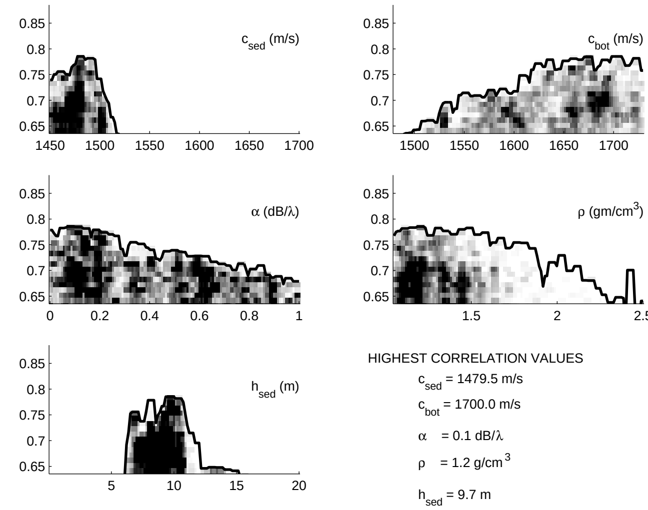

Fig. 5. MAPEX2000 HLA measured data inversion using propagation model ORCA from ping-8:05 on March 7, 2000. Correlation values (y-axis) are plotted against parameter value (x-axis) for each of 40,000 forward models included in the genetic algorithm search. A single dot is placed in each panel corresponding to the correlation and parameter value for that particular forward model computation. The darker areas indicated where the search algorithm sampled the parameter more heavily.

V. Discussion and conclusions

A comparison was shown here between matched-field geoacoustic inversion using measured data from both towed, horizontal and moored, vertical arrays. A towed acoustic system has many advantages over the moored, vertical array configuration such as easier deployments and being able to neglect range-dependence in the matched-field inversion while still mapping range-dependent seabed properties. There are also some disadvantages to the towed, array. Since the array is moving, there is less control and knowledge of the sensor positions. The towed arrays are often noisier than a moored arrays (due to flow and tow-ship noise). The horizontal array modeling and geacoustic inversion methods are not as well tested as for vertical arrays. And, the horizontal aperture usually provides less information about a wide spread of propagation angles than would a large vertical aperture. These factors indicate that, in general, the towed array data will be of lower quality and contain less information than a vertical array. If, however, the towed array data is still sufficient for geoacoustic inversion then the advantages of an easily deployed, mobile measurement system likely outweigh the disadvantages.

For the site considered here, the inverted seabed properties from the towed array compare favorably with those from the vertical array data. This was true for data taken with sound source near the vertical array—where it is expected the vertical array inversion will perform best. However, vertical array inversion difficulties were evident on a range dependent track as the source moved away from the array position. For an 11 km range dependent track the vertical array data inversion was difficult to implement because of the large change in water depth along the track—which requires range-dependent modeling. Using range-independent modeling, the vertical array inversion method did not perform well and the seabed parameters could not be determined. The range-dependent modeling problem is circumvented using the towed, horizontal array, and range dependent seabed properties are still determined since the horizontal array inversions operate on local (range-independent) environments. In this sense, the towed horizontal array inversions can out perform the vertical array inversions.

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