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RANGE-DEPENDENT GEOACOUSTIC INVERSION USING THE PARABOLIC EQUATION AND GENETIC ALGORITHMS - Application to GAIT Test Cases

TOLLEFSEN Dag

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8) ABSTRACT

Rapid in-situ assessment of sonar conditions in shallow water is an area of interest for military applications. The goal is *through-the-sensor* techniques that collect acoustic data from sonar, infer the relevant ocean environment parameters, and provide environment model data for subsequent use in sonar performance predictions or in environmentally adapted signal processing. A successful inversion method requires good solutions to several problems: how to efficiently parameterize the ocean environment, how to identify the most relevant parameters for the given mode of sonar operation, and how to most efficiently obtain estimates of geoacoustic parameters from given sonar data. In this report, an inverse method is applied to synthetic low-frequency data for two shallow-water range-dependent environments, consisting of a range-varying bathymetry over a laterally invariant seabed with depth-dependent sound speed, density and attenuation profiles. (The first two GAIT workshop 2001 test cases.) The SAGA inversion package from NURC is used with the RAM forward model from NRL. Low-frequency data within 50 Hz to 400 Hz is used for matched-field inversion on two model linear arrays (a vertical array and a horizontal array). It is found that the sound speed profiles in seabed can be estimated from acoustic data, whereas density and attenuation profiles are not well estimated. The long horizontal array provides results comparable to those of a VLA spanning the water column. A limiting factor to further applicability of range-dependent inversion methods is the execution time induced by the forward model.

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RANGE-DEPENDENT GEOACOUSTIC INVERSION USING THE PARABOLIC EQUATION AND GENETIC ALGORITHMS - Application to GAIT Test Cases

EXECUTIVE SUMMARY

Rapid in-situ assessment of sonar conditions in shallow water is an area of considerable interest for military applications. The goal is “through-the-sensor” techniques that collect acoustic data from sonar, infer or estimate relevant ocean environment parameters, and provide model data for subsequent use in sonar performance prediction tools or in environmentally enhanced signal processing methods. In the pursuit of robust applications, a set of problems are currently addressed in the underwater acoustics research community, among these: how to parameterize the ocean environment for a particular application, how to identify the most relevant parameters for a given mode of sonar operation, and how to obtain estimates of these parameters from data.

For application to low-frequency passive sonar, the seabed is the key limiting environment factor. This includes the seabed topography (bathymetry) and the geo-acoustic composition of the seabed, including depth-dependent sound-velocity, density and attenuation profiles. Remote sensing techniques based on echo-sounder can provide for relatively rapid and accurate mapping of seabed topography, but methods for rapid in-situ assessment of seabed geo-acoustic properties are under current development. Thus a considerable recent research effort has been devoted to the topic of geo-acoustic inversion in shallow water (1)(2). Inversion techniques have been developed for range-independent environments, and applied to and validated with ocean acoustic data. However, it has been realised that the assumption of range-independence, i.e. a flat seabed and no lateral variation in geo-acoustic profiles, may exclude application to many ocean areas of interest, such as the Continental Slope, the Continental Shelf Break, and environments with localized features such as salt domes.

These issues, among others, prompted the Office of Naval Research (ONR) and Space and Naval Warfare Systems Command (SPAWAR) to sponsor the “ONR/SPAWAR Workshop on Geoacoustic Inversion Techniques” in 2001. This report presents results to two of the five test problems addressed in the workshop.

1 INTRODUCTION

A key purpose of the “ONR/SPAWAR Workshop on Geoacoustic Inversion Techniques” (3) was to summarise and benchmark at the time state-of-the-art geoacoustic inversion techniques, and to challenge the research community to apply their techniques to range-dependent problems. By technique in this respect is meant (i) the use of acoustic sources and frequency content of sources, (ii) the choice and configuration of acoustic receiver arrays, (iii) the form of signal processor, (iv) the forward numerical propagation model, (v) the search or optimisation algorithm, and (vi) the method used to estimate uncertainties in the inversion results. For the work conducted in the present report[1], the purpose was not to develop new tools, but rather to gain experience with an existing inversion tool in application to range-dependent problems. Thus, a software package comprising elements (iv)-(vi), the SAGA inversion package developed at NURC (4), was used for the present study[2].

This report is organized as follows. The tools used, SAGA inversion method and RAM parabolic equation type propagation model, are briefly described in Chapter 2. Application to a down-slope test case using both vertical and horizontal arrays is presented in Chapter 3. Chapter 4 treats the shelf break test case. Some technical issues related to use of the tools are discussed in both chapters. Results are summarised in Chapter 5. The issue of numerical efficiency using PE models is addressed in an Appendix.

2 METHODS

2.1 Matched-field inversion

Matched-field geoacoustic inversion is in essence a spatial correlation process where the acoustic field measured at an array is matched with synthetic fields generated by an acoustic propagation model for a given geoacoustic model. A search over candidate models is performed, and the “true” model is taken to be the one yielding the best correlation or match with measured data. Match is here measured by the Bartlett objective function

$$E_{BI}(m) = 1 - \frac{1}{M}\sum_{k=1}^{M}\left[\frac{\left|\sum_{j=1}^{N} p_{jk}{}^{+} q_{jk}(m)\right|^2}{\sum_{j=1}^{N}\left|p_{jk}\right|^2 \sum_{j=1}^{N}\left|q_{jk}(m)\right|^2}\right] \tag{2.1}$$

with j a summation index over N hydrophones (summation in depth for a vertical line array (VLA) and in range for a horizontal line array (HLA)), k is a summation index over M frequencies, p the measured complex pressure field, q the modelled pressure field for seabed model m, and ($^+$) is the complex conjugate. The objective function takes values between 0 and

---

[1] The “Workshop on Geoacoustic Inversion Techniques” (GAIT workshop) was held in May of 2001. The work documented in this report was conducted in 2003 under project 836 SWASI-III, without knowledge of the “true answer” to the synthetic inversion problems that were addressed in the workshop.

[2] The development of inversion tools for range-*dependent* environments was not part of the project 836 SWASI-III, under which the present work was performed. The SAGA package was chosen after a review of available tools. (FFI has since 2003 adopted the use of other inversion methods and tools.)

1, with 0 indicating a perfect match. Since the number of seabed parameters and the search range of candidate values of each parameter can be large, the use of an exhaustive search method is precluded, and the application of a global optimisation method is employed.

2.2 The SAGA inversion tool

The SAGA inversion package was used for the present work. The package is based on a genetic algorithm global search method that has been successfully applied to a variety of geoacoustic inversion problems. The method will not be further described in this report; reference is made to the SAGA User Guide (4). Standard genetic algorithm parameters settings were used: replacement rate 0.50, crossover rate 0.80, mutation rate 0.05; these settings were not changed during the inversions. For each of eight independent populations, a population size of 64 was used, with a total number of 4096 forward computations for each population. This gives a total of 32.000 evaluated models per inversion.[3] Results are in this report presented in terms of Bartlett match and geoacoustic parameter values from the maximum of the posterior probability distributions (GA-Max) as estimated by the SAGA post-processor[4].

2.3 The RAM forward model

For application to problems with range-dependent environments, additional attention must be devoted to the choice of a forward (propagation) model. A suite of models for range-dependent environments is available with SAGA. These include the normal mode models C-SNAP and PROSIM (a version of ORCA) and the parabolic equation type model RAM (5). All of these treat fluid seabed environments only. The RAM model was chosen for the present work. The RAM[5] model solves the parabolic approximation to the fluid Helmholtz equation in cylindrical coordinates. The environment can be range dependent with a depth-dependent sound speed and density profile at each range. The square-root operator of the PE is expanded by a Padé approximation and the field is marched in range using an efficient split-step Fourier method. A self-starter is used for the initial field. Energy conservation is enforced at each horizontal interface. The model is run on a user-supplied numerical grid with equal-size steps at all ranges. There is no radiation boundary condition at the lower boundary, thus a false attenuating bottom must be introduced to prevent reflections off this boundary. The setup of the model numerical grid requires some attention. Ideally, a convergence test should be run on every new problem; however this may not capture the requirements for all the seabed models tested in an inversion problem. For the present application, conservative choices were set for the numerical parameters, but no rigorous convergence tests were run. A small computational grid step in depth and range,

$$dz = \lambda/16 \qquad dr = 2/3\lambda \tag{2.2}$$

with λ the acoustic wavelength in water, was used. This satisfies standard sampling criteria for this type of parabolic equation model (6). For problems with many frequencies, the grid size

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[3] For some problems, the number of populations was reduced to four, for a total of 16.000 evaluated models.

[4] In SAGA-4.1, all models evaluated in the optimisation are used in estimating the posterior distributions.

[5] RAM-geo version 1.5, downloaded from Naval Research Laboratories [ftp://ftp.ccs.nrl.navy.mil/pub/ram]

was chosen to fall within the criteria for the highest frequency of the problem.[6] The fourth order Padé approximation to the parabolic equation was used for all problems; this choice was made from an assessment of requirements for accurate modelling of propagation at some distance from the near-field.

A false bottom attenuation layer (required for PE models to absorb energy that would otherwise be reflected off the lower boundary of the grid) was set up as such: (α is attenuation and λ the wavelength in the deepest physical seabed layer): three-λ seabed false layer with attenuation α, then three-λ layer increasing to 10α, then additional three-λ layer increasing to 100α, then a final three-λ final layer increasing to 6.0 dB/λ attenuation.

2.4 Arrays and frequencies

The test cases provided data over a large grid in depth and range (3) which made possible several array designs. The data sets provided for the synthetic test cases were as follows:

- horizontal line array (HLA) at depth 25 m or 85 m, element spacing 5 m,
- vertical line array (VLA) at ranges from 0.5 km to 5 km range (spacing 0.5 km), 61 hydrophones of spacing 1 m at depths 20-80 m.

For this study two standard array configurations were selected (Table 2.1): a 60 m long VLA, and a 1000 m long HLA. Also, a short HLA was used for one test case. These were considered reasonable for realisable systems in terms of lengths and number of elements.

Parameter	VLA	HLA	Short HLA
Number of phones	61	51	41
Phone spacing [m]	1.0	20	10
Array Length [m]	-	1000	400
Array Depth [m]	20-80	25 or 85	25 or 85

Table 2.1 Standard VLA and HLA configurations used.

Data was provided at frequencies from 25 Hz to 500 Hz. The standard choice of frequencies selected for this report was: (i) Three tones at 50 Hz, 100 Hz and 200 Hz, (ii) Five tones at 25 Hz, 50 Hz, 100 Hz and 200 Hz and 400 Hz, and (iii) many frequencies within the band 50-200 Hz (to simulate a broadband source).

2.5 The Bartlett processor

For all applications, the Bartlett processor was used; either the spatially-coherent frequency-incoherent processor, Eq. (2.1), or the spatially-incoherent frequency-coherent processor,

$$E_{BC}(m)=1-\frac{1}{N}\sum_{j=1}^{N}\left[\frac{\left|\sum_{k=1}^{M} p_{jk}^{+} q_{jk}(m)\right|^2}{\sum_{k=1}^{M}\left|p_{jk}\right|^2 \sum_{k=1}^{M}\left|q_{jk}(m)\right|^2}\right] \tag{2.3}$$

---

[6] The RAM model was by default set up such that the same numerical grid must be used at all frequencies.

with j a summation index over N hydrophones, k a summation index over M frequencies, p the measured complex pressure field, q the modelled pressure field for seabed model m, and $(^+)$ the complex conjugate. This processor assumes knowledge of source spectra and amplitude, thus in practice a controlled acoustic signal. The incoherent Bartlett processor (2.1) assumes no such prior knowledge of the source. The processors will henceforth be denoted BI for the frequency-incoherent processor and BC for the frequency-coherent processor.

2.6 Test cases

The 2001 workshop provided five test cases: three using noise-free synthetic data and two using real data (3). The calibration case and two synthetic data test cases will be considered in this report.

- Test case 1 consisted of a 0.7 degree downslope from a water depth of 90 m to water depth of 150 m, with a known sound speed profile in water but unknown geoacoustic parameters of the seabed. The seabed was layered with an unknown number of layers parallel to the bathymetry.
- Test Case 2 consisted of a Shelf Break environment with 1 degree upslope from water depth 140 m to a shelf at depth 105 m. The seabed was layered with an unknown number of layers parallel to the bathymetry.
- Test Case 3 consisted of a flat bathymetry area with an intrusion in the seabed.
- Test case 4 consisted of transmission loss data (from the East China Sea). Data from 50 Hz to 800 Hz was provided. A detailed bathymetry map of the area (water depths of about 100 m) and a set of bathythermograph profiles were provided.
- Test case 5 consisted of low-frequency reverberation data (from the Gulf of Mexico). Data from 50 Hz to 6.5 kHz was provided. A detailed bathymetry map and sound speed profiles in water were also provided for this case.

The synthetic data test cases were “noise free” in the sense that no noise has been added to the synthetic data fields provided. The source depth was fixed to 20 m. Exact knowledge of the array geometry, that is, array element positions and source-array range, is assumed in all cases.

3 DOWNSLOPE TEST CASE

Test case 1 is a monotonic down-slope with a range-independent bottom with unknown layering in parallel with the bathymetry. The geometry of the test case is depicted in Figure 3.1. The sound speed profile in water is assumed known. The layering and geoacoustic profiles of the seabed are unknown. There is a small uncertainty in water depth.

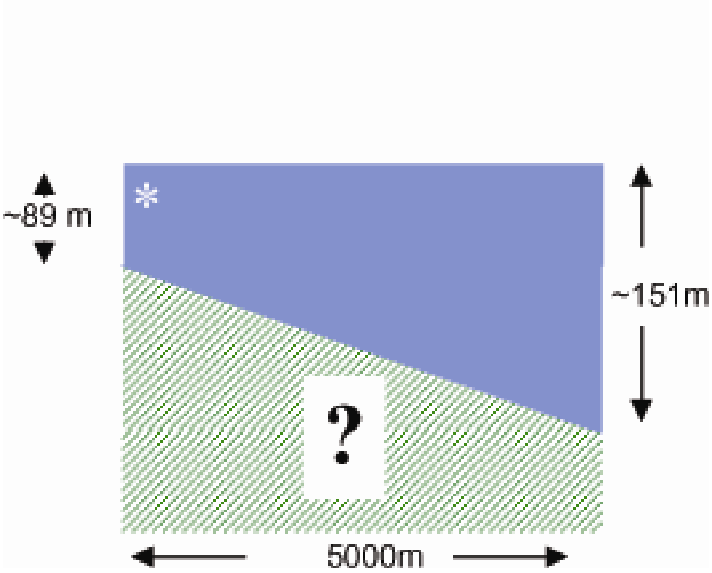

Figure 3.1 Test case 1 - Downslope

3.1 Bottom layering

The discretization of the bottom environment is an additional complicating problem; the seabed layering was not known a priori for this test case. For a fluid bottom, there are three parameters per layer (sound velocity, density and attenuation) plus the layer thickness; this increases to six parameters per layer if gradients are used within each layer. Thus the number of model parameters rapidly becomes large. The following approach was adopted: seabed models with from one to five internal depth points were generated. The same internal depth points were used for the profiles of all three parameters; this may not necessarily be correct, but seems to be a valid assumption. The search intervals for sound speed were linked between model layers (e.g. the sound speed at the top of a layer was set equal to the bottom of the layer above). Inversions were run with the number of model bottom layers ranging from two (one sediment layer over halfspace) to six (five sediment layers over halfspace).

For this work we used the long HLA, extending from 0.8-1.8 km in range, and the three standard frequencies of 50, 100 and 200 Hz. A thick attenuating layer extending to 900 m depth was used. Results in terms of energy obtained for the max-PPD model for different layering of the seabed is plotted in Figure 3.2. The energy levels off to a minimum value for N=6 layers. This may be at the limit of resolution using this data set.

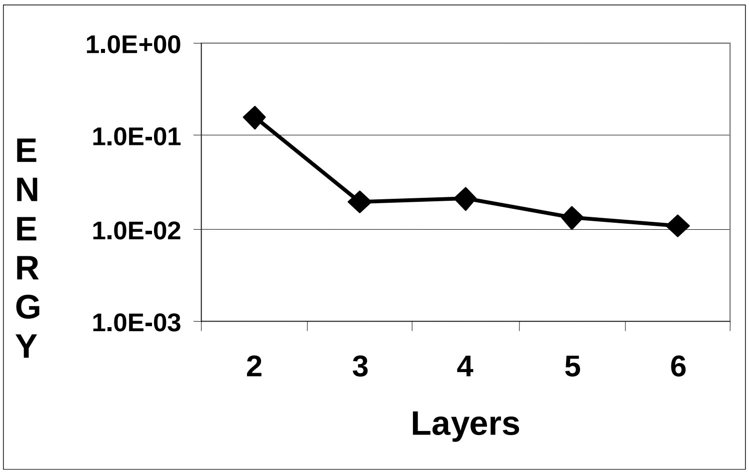

Figure 3.2 *Test Case 1. Bartlett energy for best model from inversion using N-layer seabed model, N varies from 2 to 6. Data from HLA at range 0.8-1.8 km.*

Velocity profiles obtained from the N-layer inversions are plotted in Figure 3.3.

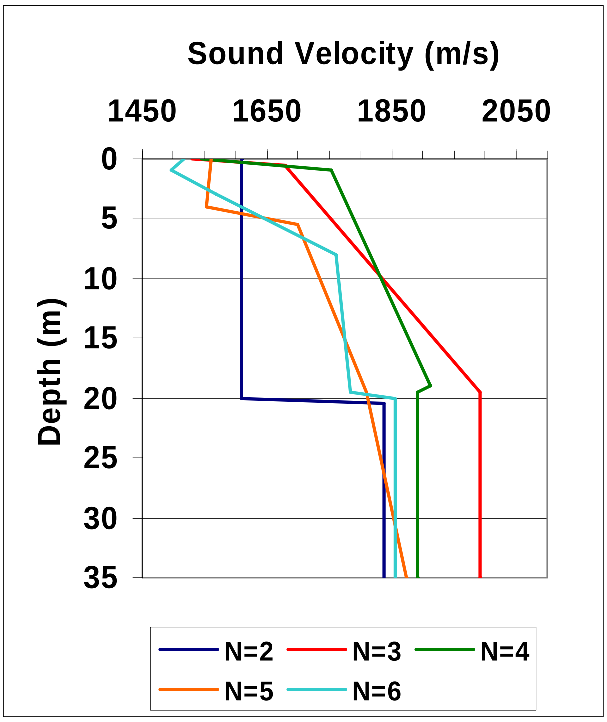

Figure 3.3 *Test Case 1. Estimates of seabed sound velocity profile using N-layer models. Inversions using HLA data at 50,100 and 200 Hz. Estimates for 2 to 6 layer seabed models.*

Only the 5- and 6-layer models resolve structure in surface sediment. Estimates of velocity in the model halfspace are in all cases above 1850 m/s, and the transition to the halfspace is modelled at depth 20 m in all but the N=5 layer case.

Based on these results, it was determined to use five depth points (a three-layer plus halspace model) in all subsequent inversions for this test case. The five depth points were set up with the search bounds indicated in Table 3.1. This models four sediment layers over a halfspace.

Depth Point	Depth interval [m]	Velocity interval [m/s]
Top of Sediment	Seabed	1500-1755
Sediment 1	+0.5 - +8.0	-40 - +214
Sediment 2	+0.5 - +16.0	-40 - +214
Bottom of Sediment	+10.0 - +41.0	-40 - +214
Sediment-Substrate	+0.5	-20 - +488

Table 3.1 Sediment layering, depth points and velocity search intervals.

For densities and attenuations, the same depth points and thus the same seabed layering were used. For these two quantities, no constraints were put on the on the profiles, thus the same search bounds were used on all profile points.

Parameter	Search interval
Density [g/cm^3]	1.40-2.03
Attenuation [dB/λ]	0.01-0.94

Table 3.2 Density and attenuation search intervals.

3.2 Horizontal Array

The HLA in standard configuration: 51 elements, element spacing 20 m, length 1000 m, depth 85 m, range 0.8 – 1.8 km, is tested and varied with respect to array depth, frequency content and processor. The cases and results in terms of Bartlett match are summarised in Table 3.3. The table also lists computer execution times.[7] The number of independent populations was eight (32.000 models tested) for the first two cases, and reduced to four (16.000 models tested) for the last two cases. Estimated velocity and density profiles are plotted in Figure 3.4. Estimated attenuation profiles will not be shown.

Frequencies or frequency band [Hz]	50,100,200	50,100,200	50, 63, 80, 100, 125, 160, 200	25-200 Δf=5 Hz
Number of frequencies	3	3	7	36
Processor	BI	BC	BI	BC
Array Depth [m]	85	25	85	85
Bartlett Match	1.10E-02	6.57E-03	1.62E-02	2.04E-02
Execution Time	6h 20min	6h 25min	7h 12min	41h 36min

Table 3.3 Test Case 1. 51-element HLA at range 0.8-1.8 km

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[7] HP-7000 series computer, two PA-RISC 2.0 processors at speed 650 MHz.

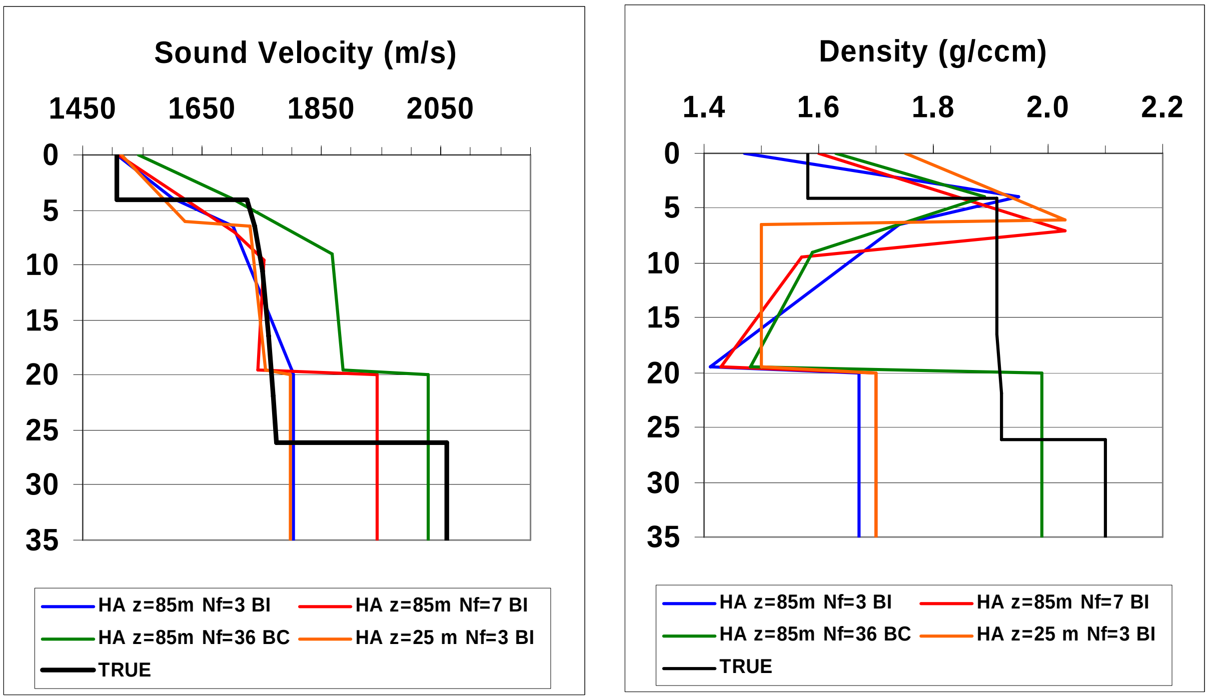

Figure 3.4 Test Case 1. Estimates of seabed velocity profile (left panel) and density profile (right panel) using HLA data (range 0.8-1.8 km) with narrowband data at 50-200 Hz (blue, red and orange) and broadband data at 25-200 Hz (green). True profiles in black.

The density profile is poorly estimated. Some structure of the upper part of sediment and the sound velocity profile to depth 20 m is resolved. The depth to the halfspace and velocity of halfspace is underestimated in all cases. The surface sediment layer (thickness 4 m) has not been well estimated. The increase in number of frequencies from three (50,100 and 200 Hz) to seven (50, 63, 80, 100, 125, 160 and 200 Hz), over the same band 50-200 Hz, did not have any noticeable effect on the estimated profile in the upper part of sediment, while there is an effect (increase of 200 m/s) on sound velocity of the halfspace. The use of the frequency-coherent Bartlett processor yielded an incorrect profile.

3.3 Vertical Array

The standard 61-element VLA configuration is used at ranges of 1 km and 2 km. The number of frequencies is also increased to seven, in all cases using the incoherent Bartlett processor. Configurations and results in terms of Bartlett match are summarized in Table 3.4. Velocity and density profiles are plotted in Figure 3.5.

The resolution of the details of the sound speed profile is similar to that obtained for the horizontal array. Similar difficulties regarding the resolution of the depth to the halfspace and the surface sediment layer as seen with use of HLA data are observed. Note that the execution time increases by a factor of two when the array is placed at a range of two km.

Frequencies or frequency band [Hz]	50,100,200	50, 63, 80, 100, 125, 160, 200	50,100,200
Array Range [km]	1.0	1.0	2.0
Bartlett Match	1.26E-02	1.76E-02	8.45E-03
Execution Time	2h 35min	5h 57min	5h 05min

Table 3.4 Test Case 1. 61-element VLA.

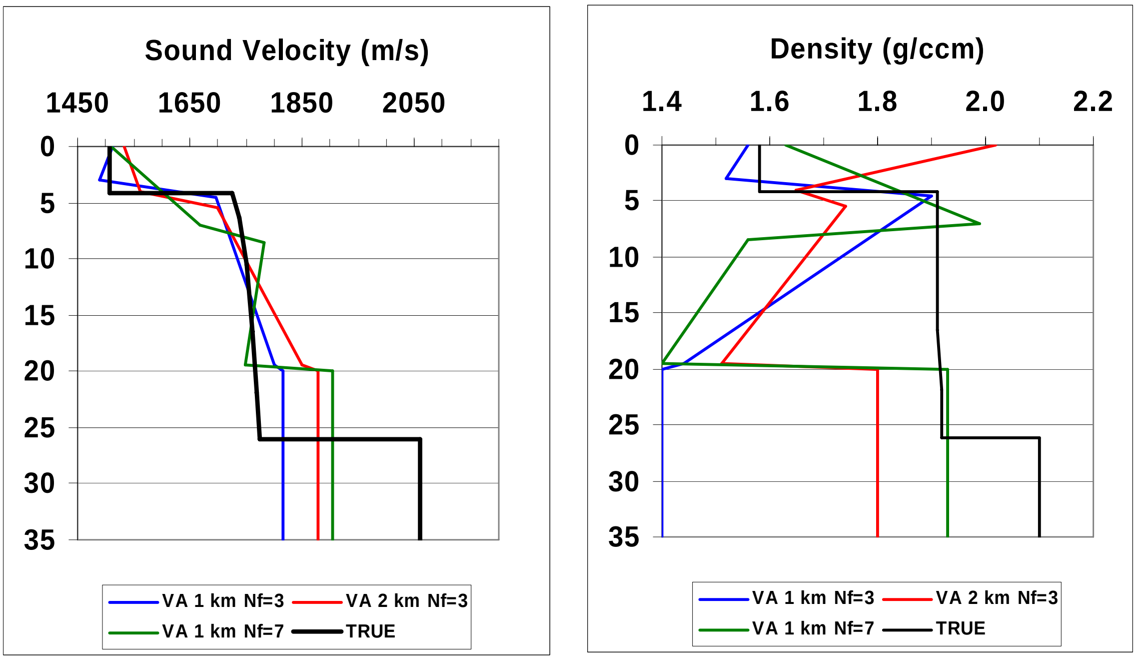

Figure 3.5 Test Case 1. Estimates of seabed velocity profile (left panel) and density profile (right panel) using data from 61-element VLA with narrowband data at 50-200 Hz. True profiles in black.

It is supposed that the relatively poor resolution obtained of the sound speed profile in the seabed for this test case likely is from several factors: (i) an incorrect parameterization of the seabed (three layers plus a halfspace was used; the true profile had six layers over halfspace), and (ii) an insufficient bandwidth of processing frequencies. When a poor choice is made with respect to these criteria, array type and placement becomes of secondary importance to the inversion results. For future work, a more robust approach to estimating the number of model layers to include in the inversions, and to the selection of frequencies (bandwidth) to include in the inversions, is desired.

4 SHELF BREAK TEST CASE

The test case consisted of an upslope from depth 140 m to a shelf at depth 105 m (a slope of 0.95 degrees) representing a Continental Slope environment. A layered bottom was assumed. The geometry is depicted in Figure 4.1.

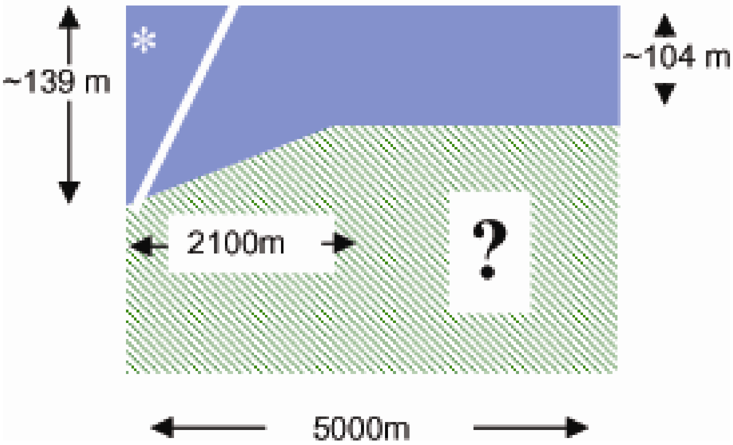

Figure 4.1 Test Case 2 – Shelf Break.

There is no variation in sound speed profile in water with range. A five-layer bottom model (four sediment layers over halfspace) was used for all inversions. For this test case, a N-layer model test was not done. Profiles were introduced also for density and attenuation. The profiles were constrained as for the downslope case (see Tables 3.1 and 3.2). Configurations including a long HLA, a VLA and a short HLA were tested.

4.1 Horizontal Array

The 51-element HLA of length 1000 m was used at three ranges: in the slope (0.8-1.8 km), at the break (1.6-2.6 km) and at the shelf (2.8-3.8 km) and for both array depths. A standard set of four frequencies (50 Hz-400 Hz band) was used with the incoherent Bartlett processor. The input parameters are summarised in Table 4.1. There were 16.000 model runs using four independent populations. Results are shown in Figure 4.2.

Frequencies [Hz]	50,100,200, 400	50,100,200, 400	50,100,200, 400
Array Depth [m]	25 or 85	25 or 85	25 or 85
Array range [m]	800-1800	1600-2600	2800-3800
Execution Time	4h 37min	7h 03min	10h 16min

Table 4.1 Test Case 2. 51-element HLA of length 1000 m. Narrowband.

Computation time increased with source-array range. Execution time for the farthest array was in excess of 10 hrs.

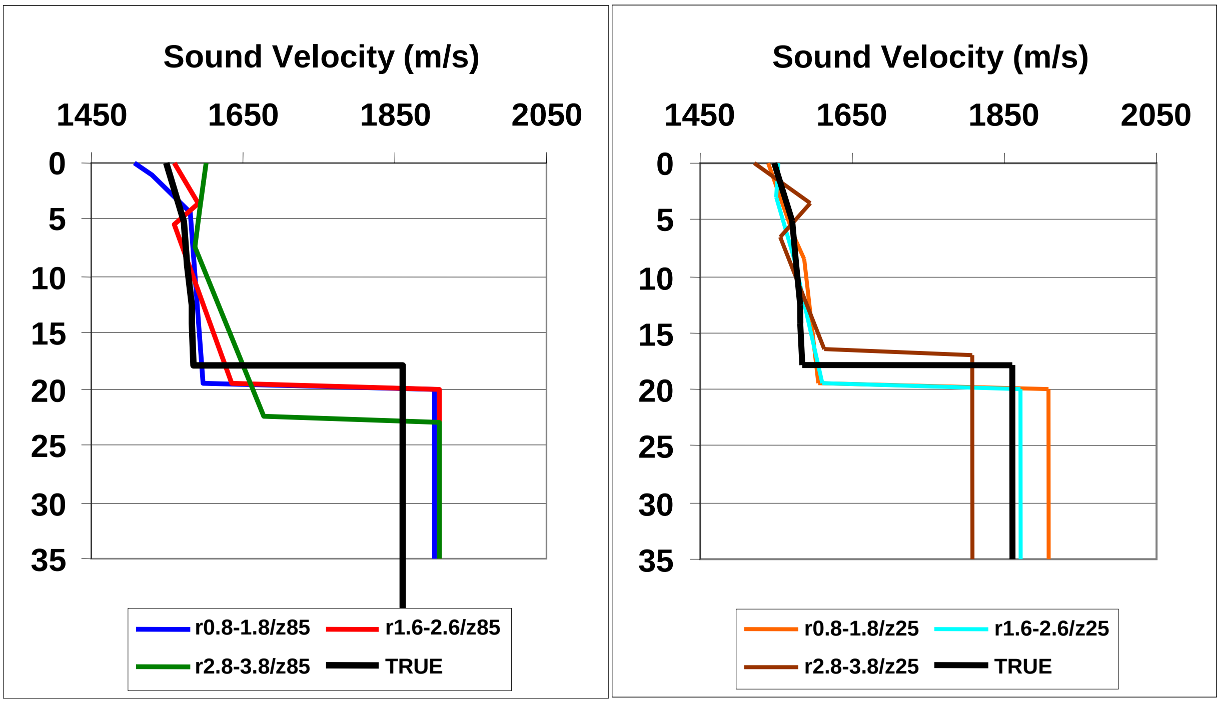

Figure 4.2 Test Case 2. Estimates of seabed velocity profile using HLA data at varying segments of the shelf break. Four frequencies (50-400 Hz). Array depth 85 m (left panel) and 25 m (right panel). True profile in black.

Results for velocity profiles are shown in Figure 4.2. A lowest energy of E=3.13E-02 was obtained for the array at 2.8 km at shallow depth. The velocity profiles are reasonably well estimated in all cases, except for details of the upper part of sediment.

For this case, a broadband computation was performed using data from 25 Hz to 200 Hz, with a total of thirty-six frequency components at a spacing of 5 Hz. The frequency-coherent Bartlett processor was used, with the array at range 0.8-1.8 km and depth 85 m. Results are shown in Figure 4.3, in the figure also compared with a corresponding four-frequency narrowband (25 Hz-200 Hz) case (in this case using the frequency-incoherent processor).

Frequencies [Hz]	25,50,100, 200	25-200 Δf=5 Hz
Array Depth [m]	85	85
Array range [m]	800-1800	800-1800
Processor	BI	BC
Execution Time	4h 40min	4 days

Table 4.2 Test Case 2. 51-element HLA at range 0.8 km. Narrowband and broadband data.

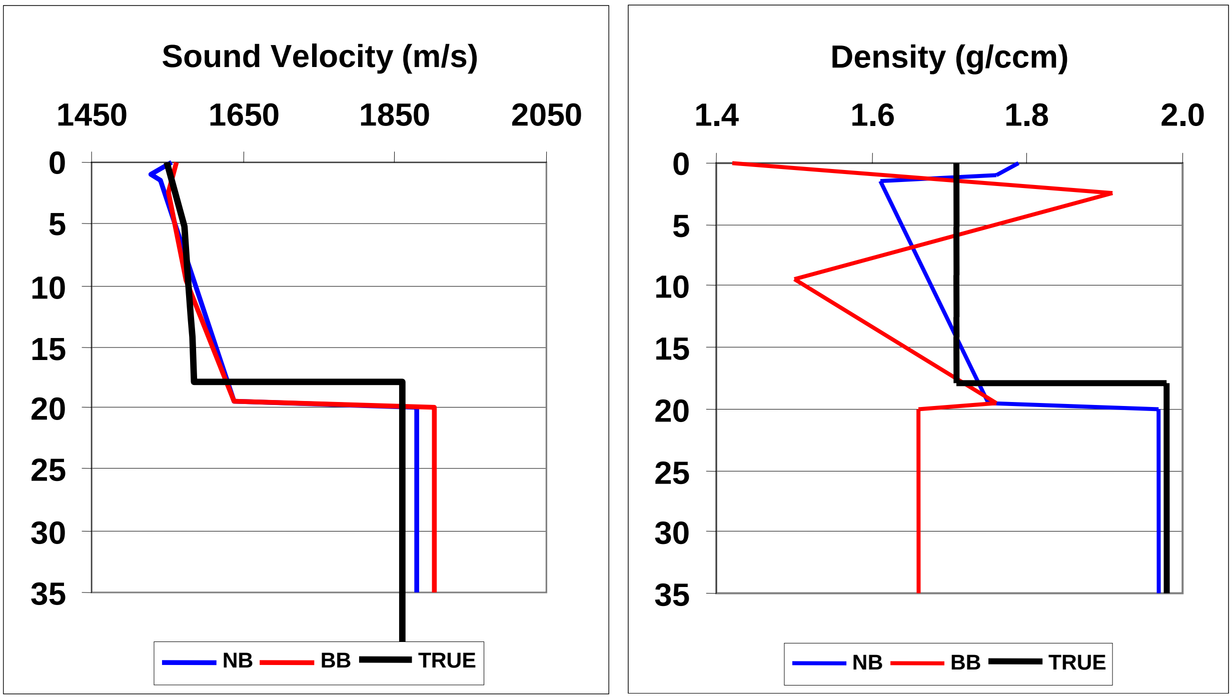

Figure 4.3 Test Case 2. Estimates of seabed velocity profile (left panel) and density profile (right panel) using HLA data (range 0.8-1.8 km) with narrowband data at 25-200 Hz (blue) and broadband data at 25-200 Hz (red). True profiles in black.

The velocities in sediment and halfspace are well estimated. The density estimates are incorrect. The broadband computation took on the order of four days computer time compared with five hours for the narrowband computations. This is clearly too time consuming to be practical and a refinement of method for use with broadband computation is warranted.

4.2 Vertical Array

The 61-element VLA with in standard configuration (element spacing 1 m) was used with three frequencies (50 Hz, 100 Hz and 200 Hz). Inversions were run with the array varying in range from 0.5 km to 4.5 km, independent inversions at each range. All inversions were run with eight independent populations testing a total of 32.000 tested models. Execution times increased with the range to the array. The energy of the best model from each inversion is plotted in Figure 4.4. The estimated velocity profiles are plotted in Figure 4.5.

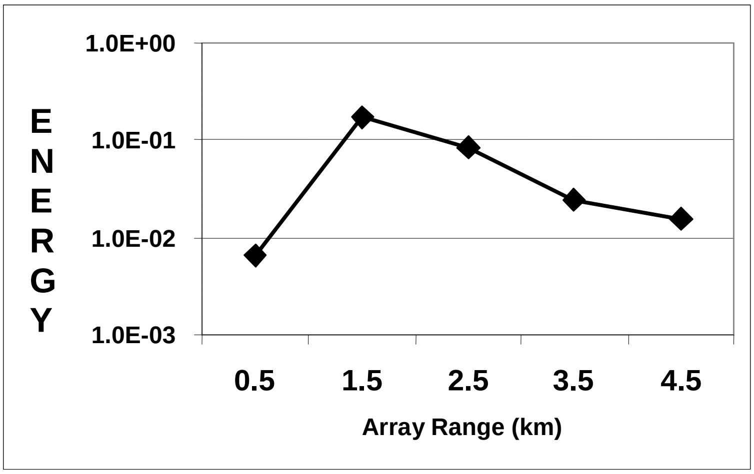

Figure 4.4 *Test Case 2. Energy of best model from inversion using data from 61-element VLA at varying range. Three frequencies (50,100 and 200 Hz) with the incoherent broadband Bartlett processor.*

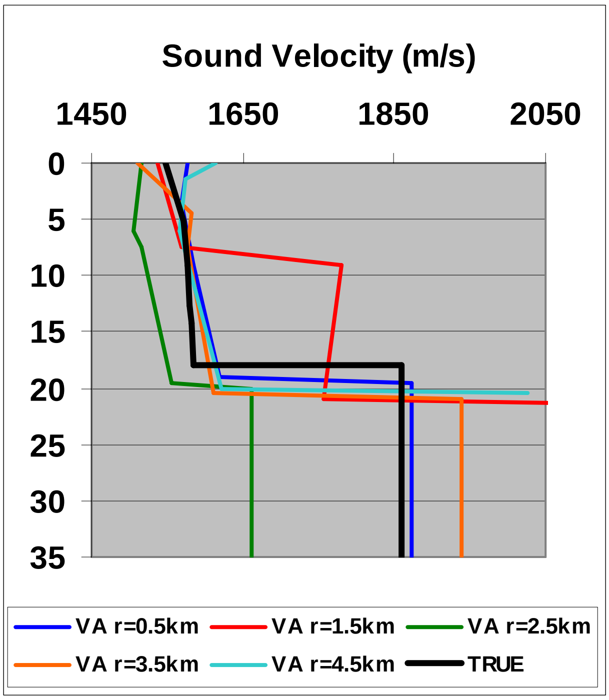

Figure 4.5 *Test Case 2. Estimates of seabed velocity profileusing data from 61-element VLA at varying range. Three frequencies (50, 100, 200 Hz). True profile in black.*

The true velocity profile is most closely followed using the closest array at 0.5 km (in the slope) and the array at 3.5 km (on the shelf). Wrong profiles are obtained using the VLA at all other ranges. A lowest energy of E=6.4E-03 was obtained for the array at closest range.

Also, with the VLA, the number of hydrophones was reduced to 17, thus using a hydrophone spacing of 5 m over depths 20-80 m. Three frequencies at 50, 100 and 200 Hz were used with the incoherent broadband Bartlett processor. Results are plotted in Figure 4.6.

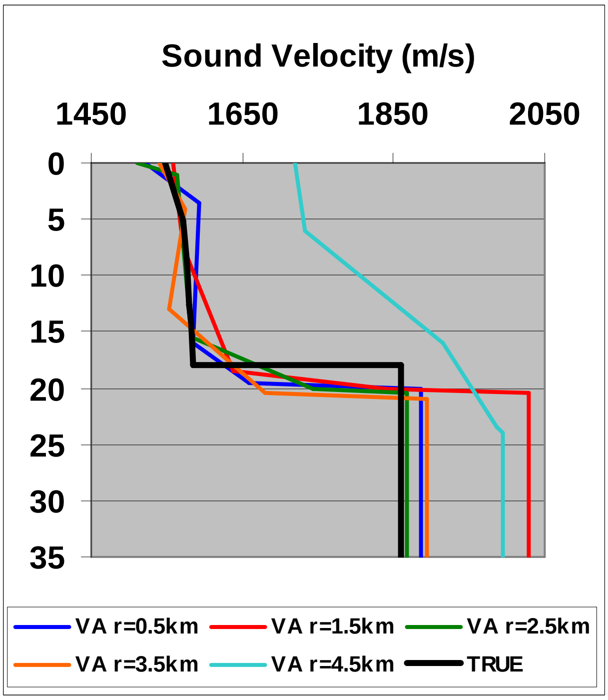

Figure 4.6 Test Case 2. Estimates of seabed velocity profile using data from a sparse 17-element VLA at varying range. Three frequencies. True profile in black.

Estimates are fairly consistent, except for the array at range 4.5 km, and more consistent than the estimates obtained with the full 61-element array. The reduction in execution time is by a factor of 3.5, since the acoustic field now has to be propagated for seventeen rather than 61 model depths.

4.3 Short horizontal array

A horizontal array of length 400 m (41 elements, spacing 10 m) is used at varying range along the slope, from 0.4 km to 1.6 km, and for two depths. Three frequencies of 50 Hz, 100 Hz and 200 Hz are used with the incoherent broadband Bartlett processor. Inversions are for eight populations testing a total of 32.000 models. The energy of the best model from each of the six inversions is plotted in Figure 4.7. Estimated velocity profiles are shown in Figure 4.8 for the deep array depth of 85 m (results for array depth of 25 m are not shown; these results were poorer in that the structure of the upper part of sediment was not as accurately resolved).

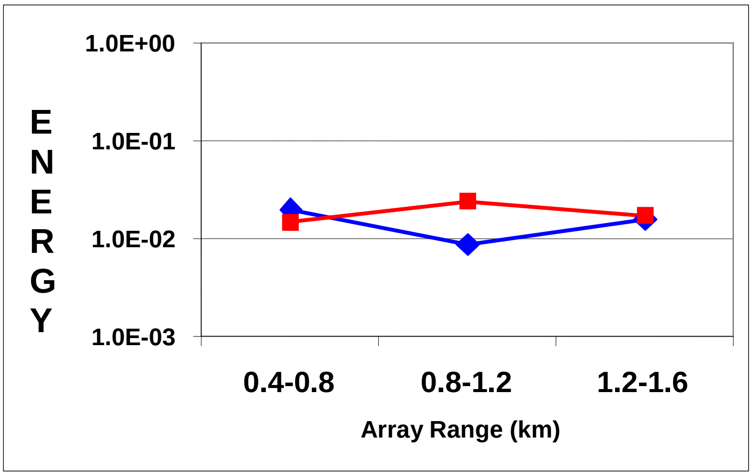

Figure 4.7 Test Case 2. Energy of best model from inversion using data from 41-element HLA at shallow depth (red) and deep depth (blue) depths at varying range. Three frequencies (50,100 and 200 Hz) with the incoherent broadband Bartlett processor.

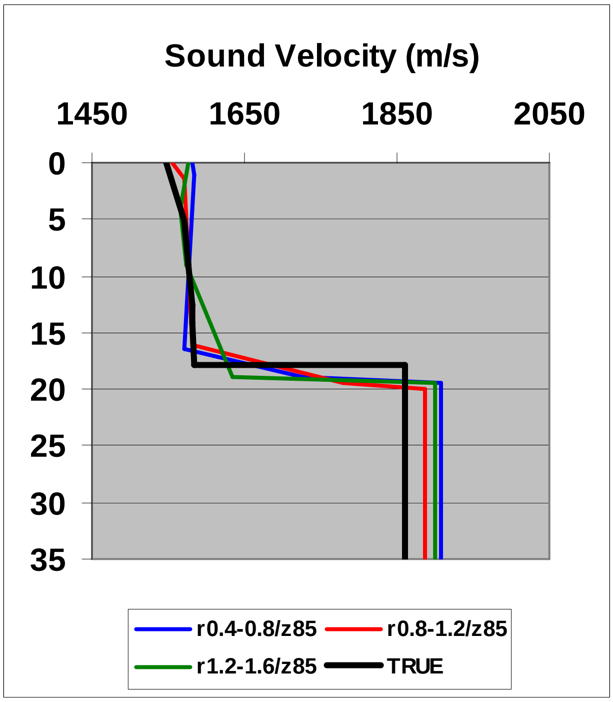

Figure 4.8 Test Case 2. Estimates of seabed velocity profile using data from short HLA at varying ranges of the shelf break. Three frequencies. Array depth 85 m. True profile in black.

Best results were obtained using the array at 85 m depth. A lowest energy of E=8.7E-03 is obtained for the array at range 0-8-1.2 km. Note that as the array is moved out in range, it is moved to shallower depth, from a mean water depth of 130 m to a mean water depth of 116 m. Execution time was four hours for the array at shortest range, increasing with range. Estimates of density and attenuation profiles (not shown) were poor. The use of a short HLA at short range should also be studied with use of broadband data and the coherent Bartlett processor, to simulate situations where a controlled source is used with a towed array (7).

5 SUMMARY

Matched-field inversion for seabed geoacoustic properties has been studied with synthetic low-frequency data for two range-dependent environments. Two test cases from the GAIT 2001 workshop were addressed: a down-slope bathymetry with a seabed of unknown layering and unknown seabed properties in parallel with the slope, and a shelf break environment with an upslope followed by a shallow shelf, also with a seabed of unknown properties in parallel with the seabed. For both cases, two fixed linear array configurations were used: a 61-element VLA of length 60 m, and a 51-element HLA of length 1000 m. The inversion tool applied was the SAGA genetic algorithm global search method with the RAM parabolic equation forward propagation model. Data at frequencies within 25-400 Hz was selected for use with the frequency-incoherent, spatially-coherent Bartlett processor. A limited set of source-array geometries were tested, thus general conclusions in how to optimally design matched-field inversion experiments should not be inferred from results of this report. However, a general result of potential interest is that a long HLA provided inversion results comparable to those of the traditionally more used VLA. A short HLA also gave good results, and it could be of interest to further study the performance of short HLAs with broadband sources, to simulate the concept of using towed array data for MFI.

The seabed parameter profiles obtained by inversion were compared with the true profiles. In general, the velocity versus depth profile was recovered to some accuracy, while estimates of density and attenuation profiles were poor. An inherent problem of the inversion method as employed in this report was the inability to resolve the exact layering structure of the seabed. (The layering structure was not known a priori.) Configurations using arrays at long range and/or high frequencies induced considerable computational efforts, with inversion runs taking up to a day for the computationally most intensive case. This does at present impose a limitation on the utility of the inversion method as applied here. A broadband computation took on the order of four days computer time which also clearly is too time-consuming to be practical. A further development of methods for use with broadband data is warranted. Some measures that can be invoked in order to reduce the computation load when using a parabolic equation type forward model were mentioned, yet it is apparent that other inherently more rapid types of propagation models, such as ray trace, should be evaluated for future use in range-dependent inversions. A final shortfall of the present analysis is the lack of a discussion of model parameter uncertainties, which can be an important additional input to sonar prediction tools and environment databases.

APPENDIX

A CALIBRATION

Synthetic fields generated by a high-fidelity acoustic propagation model were supplied with the geoacoustic parameters of the seabed. This enabled the user to generate synthetic fields for the provided environment using his forward model and compare the match. Alternatively, an inversion could be run to check to what accuracy the provided model parameters could be estimated. The second approach was adopted herein. The model consisted of a sediment layer with constant gradient sediment of thickness 35 m overlying a hard basement. For sound speed, two internal points at 3 m and 10 m into sediment were introduced. Such points were later used when bottom layering was unknown. The total number of inversion parameters was thus: two bathymetry points, five sound speed points, three densities, three attenuations, a total of thirteen parameters. The two standard vertical and horizontal array configurations were used. A total number of 32.000 forward models were tested. Results obtained by inversion (best model from SAGA) are summarised in Table A.1.

Parameter	**Unit**	**VLA**	**HLA**	**TRUE**
Bathymetry 1	m	106.0	105.0	105.0
Bathymetry 2	m	160.0	160.0	160.0
Sediment 1 p-vel	m/s	1560.6	1500.0	1535.0
Sediment 2 p-vel	m/s	1566.6	1561.0	1541.4
Sediment 3 p-vel	m/s	1555.6	1559.0	1556.4
Sediment 4 p-vel	m/s	1609.6	1601.0	1610
Basement p-vel	m/s	1849.6	1801.0	1800
Density 1	g/cm^3	1.45	1.48	1.550
Density 2	g/cm^3	1.72	1.65	1.590
Basement Density	g/cm^3	1.89	1.73	1.950
Attenuation 1	dB/λ	0.099	0.167	0.1228
Attenuation 2	dB/λ	0.010	0.010	0.0322
Basement Atten.	dB/λ	0.591	0.118	0.036
Bartlett Match		1.44E-02	1.01E-02	

Table A.5.1 Results from calibration test case. Standard VLA and HLA configurations, Data at three frequencies (50, 100 and 200 Hz), Bartlett processor. Parameter values are best model estimates by SAGA.

B NUMERICAL EFFICIENCY

In matched-field inversion of real data there are several sources of “noise”, not only in the acoustic data but also in the geoacoustic model (layering, choice of parameters) and in the forward model. These points were discussed in Ref. (8), where it is argued that for application to MFI one can for practical applications relax on the numerical requirements in running the forward model without introducing significant additional noise in the inversion. The gain can be significant in reduced execution time. For the short 41-element HLA at depth 85 m and short range (0.4-0.8 km), inversions were run using coarser grid steps in range and depth, and fewer terms in the Padé expansion. The coherent Bartlett processor with 61 frequency components from 100 Hz to 400 Hz was run for 16.000 forward models in each inversion. The scenarios are summarised in Table B.1.

Range step [m]	5.0	10.0	20.0	100.0	5.0	10.0
Depth step [m]	0.5	0.5	0.5	0.5	0.5	2.0
Bartlett match	7.82E-02	7.78E-02	8.77E-02	0.2251	7.82E-02	0.2344
Computation time	38 hrs	30 hrs	25 hrs	19 hrs	38 hrs	5h 40min

Table B.1 Results from test case 1, short-HLA, and coarse numerical grid.

The results indicate that one can obtain results in reasonable agreement with the true profile, at least for the most sensitive parameter, using a coarser range step than would be required from normal guidelines for a normal run of the propagation model. It is difficult to assess in beforehand the effect of running a coarse grid on the total performance of an inversion.

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