Performance Comparison Between Vertical and Horizontal Arrays for Geoacoustic Inversion

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***Abstract*—Most of the research on model-based geoacoustic inversion techniques has concentrated on data collected using moored vertical receiver arrays. However, there are many advantages to considering geoacoustic inversion using a towed horizontal array. Towed arrays are easily deployed from a moving platform; this mobility makes them well suited for surveying large areas for sea-bed properties. Further, if a model-based geoacoustic inversion scheme uses both a towed source and array, the separation between the two can be kept short, which reduces the requirement for range-dependent modeling. Range-independent modeling is used for inverting all the horizontal array data considered in this paper. Using the Inversion Techniques Workshop Benchmark Test Cases, the performance of a horizontal (simulated towed) and vertical arrays are compared and found to be very similar. However, it will be shown that, for Benchmark Test Case 3, where the bathymetry is flat and a hidden bottom intrusion exists, a towed horizontal array is ideal for determining the range-dependent sea-bed properties. The practical advantages of using a towed array are clear and the purpose of this paper is to show that the performance is similar (and in some cases better) than using moored vertical arrays.**

***Index Terms*—Geoacoustic inversion, horizontal array, towed array.**

I. Introduction

THE INVERSIONS Techniques Workshop (ITW) was organized to test and compare a variety of acoustic methods for estimating sea-bed properties in the ocean. The workshop organizers designed three "blind" test cases in which participants were given acoustic data and asked to apply their algorithms and estimate the bottom characteristics. The participants were then asked to present their findings at the workshop before the answers were revealed. An overview of the workshop and test cases is given in [1]. The three ITW acoustic data sets considered in this paper were simulated using realistic bottom characteristics [1] and, in this way, ground truth was known. The geometry for the test cases is shown in Fig. 1. Better inversion results can be obtained with the solutions in hand since knowing the parameterization of the sea bed (e.g., number of layers, isospeed versus gradients in the layers) allows for exact modeling and the search can be continued until a perfect match is found. However, the blind results are more interesting since, in practice, little is usually known about the sea bed prior to measurements and inversion. Therefore, the inverted sea-bed properties presented in this paper are those given at the ITW before the solutions were distributed to the participants.

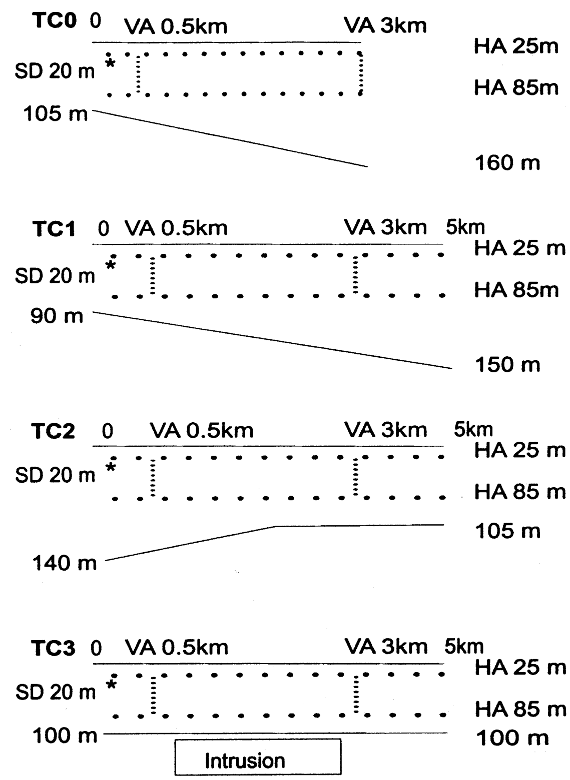

Fig. 1. Bathymetry and array geometry for the ITW test cases. (HA indicates horizontal array, VA indicates vertical array, and SD indicates source depth.) Top panel: calibration case TC0 and below are TC1, TC2, and TC3. No information about the sea-bed properties were given to participants (including no information about the location of the intrusion in TC3).

The purpose of this paper is to compare geoacoustic inversion using data from moored vertical line arrays (VLAs) and from horizontal line arrays (HLAs). The ITW benchmark test cases were generated synthetically using propagation-model RAM [2] and provide an excellent data set for making the comparison. Matched-field processing (MFP), geoacoustic inversion techniques, will be used to invert these data (both VLA and HLA). Matched-field processing geoacoustic inversion is a technique that has shown success in characterizing the sea bed for the

Manuscript received November 11, 2002; revised April 11, 2003. Initial work was supported by the SACLANT Undersea Research Centre, La Spezia, Italy, and was continued with support from the Office of Naval Research.

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Digital Object Identifier 10.1109/JOE.2003.816697

most important parameters for propagation prediction. This remote-sensing inverse method uses down-range acoustic measurements to infer properties of the sea bed. Computer simulations model down-range acoustic responses to different sea-bed types and efficient search algorithms are applied to find the environment giving an optimal match between modeled and measured data.

For MFP inversion, a towed HLA has several practical and modeling advantages over a VLA.

1) Towed arrays are easy to deploy from a ship and are widely available.
2) If used with a towed source, the requirement for range-dependent modeling in the MFP inversion is eliminated, because the sea bed and bathymetry can usually be assumed constant over the short distance separating source and HLA.
3) If HLA and sound source are kept at short-range separation, MFP degradation due to variability that is not possible to include in the modeling is eliminated (e.g., water column, sound speed, and sea–surface variability).
4) A towed system is advantageous because, as the array moves along the track local sea bed, properties are estimated. When combined along the track, the result is a mapping of possibly range-dependent properties. For example, in Test Case 3 (see Fig. 1), if the measurements are taken with a VLA located at a 5-km range, then the inversion results represent an average of the sea bed over the entire track.

With a towed array, measurements are made over a short range and local sea-bed properties are determined all along the track, yet the full range-dependent features are the final result. Inversions for a range-dependent feature will be illustrated with an example in Section IV-D. There are some drawbacks to the towed-array approach too. The motion of a towed array and uncertainty in hydrophone positions creates potential sources of inversion errors. The towed array typically has less vertical aperture and, therefore, will offer less information from different propagation angles than do vertical arrays. A discussion about effective vertical aperture from horizontal arrays can be found in [3]. Some parameters, such as attenuation, might be better estimated from far-field rather than near-field measurements (e.g., if the source and array are towed together, there are limits to the amount of range separation between them). Although much less studied, measured towed array data have been successfully inverted for sea-bed properties [4], [5]. In [5], a comparison was made between inversion results from measured HLA and VLA data. Unlike [5], in this paper, the focus is on simulated data from the ITW benchmark test cases. It is useful to study and compare HLA and VLA performance with the ITW test cases since the data is from noise-free simulations and exact sea-bed properties are known, allowing for direct comparisons between inversion results and ground truth.

The VLA configuration makes sense from a measurement viewpoint, since the propagating acoustic field is received at many angles and, therefore, contains information about how an acoustic field interacts with the sea bed at many angles. However, from a practical sense, as the range increases between source and array, the range dependence in the environment can degrade the prediction capability of the matched-field processor. The degradation is primarily due to inaccuracies in the environmental inputs to the propagation model (e.g. bathymetry, water column sound speed, or sea-bed properties). While bathymetry might be known in advance, details of the water column are difficult to obtain, as are the sea-bed properties (the reason for doing geoacoustic inversion). Further, with either the source or array moored in a fixed location, the inverted bottom properties will be spatially averaged. This is problematic in cases where range-dependent sea-bed properties exist. In these cases, averaged sea-bed properties may not correctly capture the behavior of the field (i.e., when used for modeling, this can lead to wrong field predictions). The advantage of using an HLA over a VLA will be shown when examining Test Case 3.

II. ITW Test Cases

Six test cases were provided to the workshop participants. Test Case 0 (TC0) was a calibration case in which both the acoustic data and all environmental information were given to participants. TC0 was used for verifying correct interpretation of the data (e.g., sign conventions). This calibration case was used solely for this purpose and will not be discussed further here. Test Cases 1, 2, and 3 (TC1, TC2, and TC3) were simulated data sets and Test Cases 4 and 5 (TC4 and TC5) were from measured data. The purpose of the work presented here is to analyze the performance of towed (horizontal) array inversion and to then compare this using vertical array data. This reduced the possible data sets for consideration to TC1, TC2, and TC3. A comparison of vertical and towed arrays for geoacoustic inversion using measured data can be found in [5].

The water column sound speed properties were the same in TC1, TC2, and TC3. The surface sound speed was set at 1495 m/s and decreased with depth with a gradient of -0.04 1/s. The bathymetry in TC1, TC2, and TC3 were all different and are shown in Fig. 1. In each case, there was a possible error in the given bathymetry of ± 1 m. Nothing was known about the bottom properties except that, for TC1 and TC2, the properties did not vary with range over the track and, for TC3, there was range dependence in the sea-bed properties.

The same approach was used to analyze each of the test cases. The vertical array data was taken with a 500-m source–receiver separation and the horizontal array data was taken at the 85-m depth. For both HLA and VLA data, the sound source was at 20 m. For the VLA, receivers were taken at all available depths 20–80 m in 1-m increments. The HLA geometry was taken to be similar to a towed array: hydrophones taken from 300 to 600 m from the source at 5-m spacing. Inversion results comparing the VLA and HLA were presented at the workshop for TC1, TC2, and the first 1 km of the TC3 track; these are shown in Section IV.

TC3 offered an excellent opportunity to explore some of the benefits of a towed array measurement geometry. In TC3, there was range dependence in the bottom, although the bathymetry was flat. That is, an intrusion was introduced into the sea bed (see Fig. 1). Unfortunately, the workshop did not provide simulated towed array data. However, they did provide “horizontal array" data consisting of data every 5 m from 5–5000 m in range with the source fixed. For TC1 and TC2, the provided data was perfect to simulate a towed array by sampling the horizontal array as previously indicated. However, using the same approach for TC3, only the bottom properties in the first few kilometers (before the intrusion) could be determined.

To show how the TC3 intrusion can be easily uncovered from towed array data, an extension was made of the workshop data to simulate a towed source and receiver over the track. This, of course, was only possible after the workshop and ground-truth bottom properties were handed out to participants. The simulation was carried out using the same propagation model (RAM) as used to generate the workshop data. This data was then inverted at various ranges along the acoustic track; these results are presented in Section IV-D.

III. Inversion Method

Matched-field geoacoustic inversion has several components: 1) the measurement geometry (configuration); 2) the forward propagation model; 3) the assumed geoacoustic model for the site; 4) the cost function; 5) the search algorithm; and 6) a post-inversion estimate of the quality of the results and errors. These components are briefly described below.

1) Determining the ideal experimental geometry is difficult since this often depends on the environment and probably requires simulations to estimate ideal measurements. This is complicated because many of the errors and uncertainties found experimentally are hard to duplicate in simulation. Sometimes the measurement geometry is constrained by practical considerations (such as length of arrays and number of hydrophones) or, in the case of the workshop, the geometry was mostly defined by the data made available.

For the horizontal array, the length could have been taken as 5000 m; this likely would have improved results since nearly all propagation angles would have been measured. However, to be more realistic, a 300-m array was used (i.e., hydrophones from 300 to 600 m at 5-m spacing). Deeper horizontal arrays should receive sea-bed reflected acoustic signals over a greater spread of propagation angles and are, therefore, preferred to shallow arrays so the 85-m array depth was chosen. The frequencies used for inversion were 30–500 Hz with a 10-Hz increment.

The vertical array data provided was realistic and all hydrophones were used covering depths of 20–80 m with 2-m spacing. The source–receiver distance was taken at 500 m to take advantage of high-order modes that are still propagating and have strong interaction with the sea bed and, therefore, contain useful information for inversion. However, in some cases this might not be optimal and should be balanced with longer range measurements that allow for the acoustics to have more interactions with the bottom, thus helping in determining some of the loss parameters. The frequencies chosen were 50–450 Hz in 100-Hz steps. Fewer frequencies were used than for the horizontal array, but this was to keep the computer run times approximately the same between the HLA and VLA inversions. Further, adding additional frequency content did not appear to greatly change the inversion results.

TABLE I

Sea-Bed Parameter Labels and Minimum and Maximum Values in the Search Space for all ITW Test Cases Considered. Density Is Assumed Constant Through the Sediment Layers and Subbottom. Attenuation Is Given for Layer 1 and the Layer-2 Value Extends to the Subbottom. Sound Speeds Refer to Compressional Acoustic Waves and Attenuation Is Given in Units of Decibels per Wavelength

Parameter	Minimum	Maximum
Layer-1 thickness: h_{sed1} (m)	0.0	10
Layer-1 speed: c_{sed1} (m/s)	1480	1650
Layer-1 Atten.: α_{sed1} (dB/λ)	0.0	1.0
Layer-2 thickness: h_{sed2} (m)	10.0	40
Layer-2 speed: c_{sed2} (m/s)	$c_{sed1}+5$	$c_{sed1}+300$
Layer-2 Atten.: α_{sed2} (dB/λ)	0.0	1.0
Sub-bot. speed: c_{bot} (m/s)	$c_{sed2}+5$	$c_{sed2}+300$
Sub-bot. Atten.: α_{bot} (dB/λ)	0.0	1
Density: ρ (g/cm^3)	1.0	2.5

2) The propagation model should be chosen so that the modeling approximations are valid for the experimental conditions (e.g., near- versus far-field propagation and the adiabatic approximation [6]). Both the HLA and VLA are relatively close to the source and the near field cannot be ignored. For the VLA inversion, the same RAM model that was used to generate the workshop data was used for inversion. For the HLA, the broadband, complex normal mode model ORCA [7] was used. This code was chosen since it is valid in the near field and was already set up for inversion of towed array data. Previous modeling results showed a good comparison between ORCA simulations and measured towed array data [5]. As the ORCA model was set up, it could not include range dependency in the environment. To account for the changing bathymetry, an effective environmental parameterization was needed. This meant assuming a flat bathymetry and allowing the horizontal array to tilt. That is, at each receiver range along the array, a flat bathymetry can produce approximately the same field as one having a sloping bathymetry, as long as the receivers are allowed to change depth to maintain the same relative position in the water column. This topic of effective parameters is described in [8]–[10] and is applied to geoacoustic inversion and the workshop test cases in [10].

3) The geoacoustic model contains the underlying assumption about the structure of the sea bed. This is then implemented through a set of parameters used as input to the propagation model. No information was provided from the workshop organizers about the bottom properties, so a model having two layers over a half-space was chosen. The decision to use a two layer over a half-space model was made after some preliminary analysis on the TC1 case showed some sensitivity below the top layer. However, a two-layer model led to ambiguous results for TC2; this case was re-run using a single layer over subbottom. After establishing the geoacoustic model, the search bounds were set using realistic minimum and maximum values for sediments and subbottoms. The search parameters and search bounds for the geoacoustic parameters are given in Table I. The uncertainty in the bathymetry of ± 1 m was also included as a free parameter in the search.

4) The cost function quantifies the agreement between the measured and modeled data. In this paper, the measured data is also modeled (i.e., simulated), but for clarity will be referred to

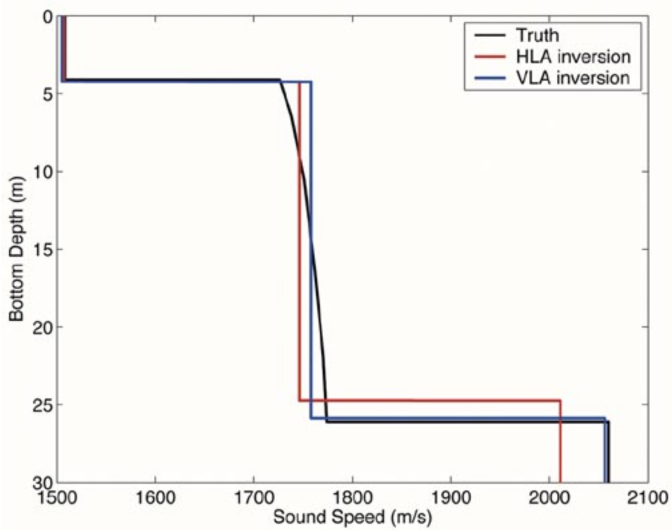

Fig. 2. Sea-bed layering and sound speed from ground truth (black line), HLA (red line), and VLA (blue line) inversions for TC1. The geoacoustic model for inversion was two layers over a subbottom and the ground truth has many layers.

as the measured data. This cost function correlates the modeled and measured pressure fields over the array of hydrophones and the magnitudes are summed over frequency as

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

In (1), 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). This correlator takes on a value of 1 for two identical signals and 0 for completely uncorrelated signals.

5) The search space for these inversions is enormous and the cost function typically has many local minima, which necessitates 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 [11], [12]. The inversions in this paper use a genetic algorithm from the SAGA inversion package [13]. 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.

TABLE II

RESULTS FROM INVERTING BOTH HORIZONTAL AND VERTICAL ARRAY DATA FOR TC1 (BEST-FIT SOLUTION). NOTE, THE GEOACOUSTIC MODEL FOR INVERSION HAS TWO LAYERS OVER A SUBBOTTOM AND THE GROUND TRUTH HAS MANY LAYERS. FOR COMPARISON, LAYER 1 AND THE SUBBOTTOM ARE COMPARED DIRECTLY WITH THE GROUND TRUTH FIRST AND LAST LAYERS AND THE MIDDLE LAYERS ARE COMBINED INTO A SINGLE LAYER WITH SOUND SPEED AND ATTENUATION PRESENTED AS A RANGE OF VALUES AND COMPARED WITH INVERTED LAYER 2

Parameter	HLA	VLA	Truth
Layer-1 thickness: h_{sed1} (m)	4.2	4.2	4.1
Layer-1 speed: c_{sed1} (m/s)	1507	1505	1508
Layer-1 Atten.: α_{sed1} (dB/λ)	0.2	0.1	0.1
Layer-2 thickness: h_{sed2} (m)	20.7	21.7	22.0
Layer-2 speed: c_{sed2} (m/s)	1746	1758	1726–1774
Layer-2 Atten.: α_{sed2} (dB/λ)	0.5	0.5	0.69–0.041
Sub-bot. speed: c_{bot} (m/s)	2011	2056	2060
Density: ρ (g/cm^3)	1.6	1.8	1.58–2.1

6) Inversion errors are usually difficult to assess due to the difficulty in establishing "ground-truth" values for the geoacoustic parameters. However, for this workshop, "ground truth" is known for TC1, TC2, and TC3. A simple approach to estimating how well a parameter is determined is to plot the correlation value [from (1)] 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. Details about different ways to obtain estimates of the *a posteriori* probability densities for each parameter can be found in [14]–[16].

IV. RESULTS FROM THE ITW TEST CASES

The ground-truth sea bed could not be matched exactly with the inversion, since the geoacoustic model (used for inversion) had only one or two layers over subbottom and the ground-truth sea bed had many layers. This made the comparisons a little more difficult, so the inversion results from the HLA and VLA will be presented in several ways. First, a plot showing the layering structure and bottom sound speed is used to roughly determine which layers from the ground-truth sea bed correspond to the layers from the inversion. Once the layering correspondence is determined, the results are presented for all the sea-bed parameters in tabular form. In addition, a plot of correlation values versus parameter values as described in Section III, 6) is shown to illustrate and compare the relative sensitivities between the HLA and VLA. Finally, transmission loss plots are used as another way to assess inversion quality.

A. TC1

The inverted layering structure and sea-bed sound speed is shown along with the ground-truth values in Fig. 2. The figure indicates that the ground-truth sea bed for TC1 has a similar parameterization as the geoacoustic model used for inversion (i.e., two layers over a subbottom) with some differences. The ground-truth sea bed has a distinct top layer of 4.1 m overlying several layers with sound speed that varies from 1726 to 1774 m/s overlying a subbottom of 2060 m/s. To present all the

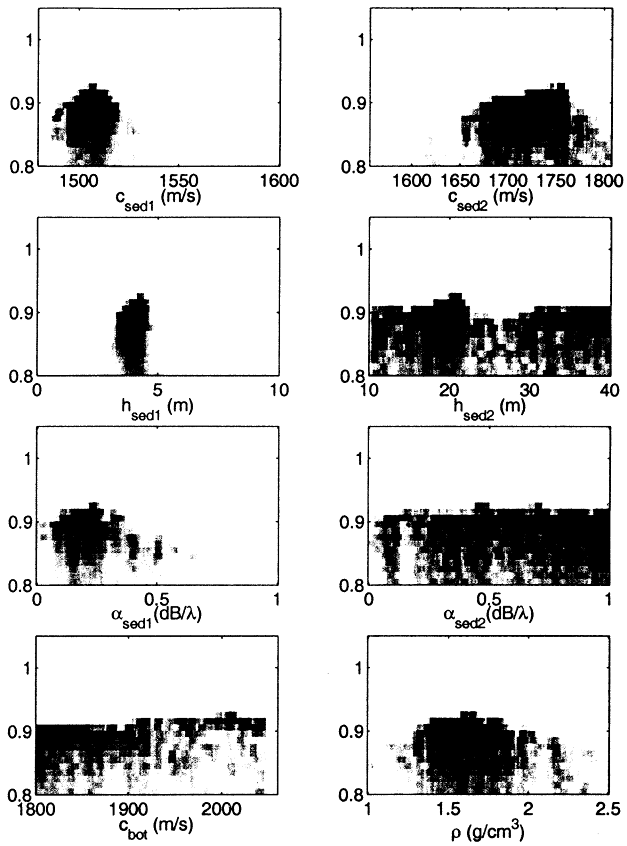

Fig. 3. Cost function values for TC1 are plotted for the HLA for each of 40 000 environments included in the genetic-algorithm search. Each point on the plot is the correlation value for that particular parameter value. More densely populated areas show where the genetic algorithm is finding higher correlation scores. A peak indicates where a parameter is well determined and a flat distribution indicates little sensitivity. (For this inversion, $h_{\rm sed2}$ was defined as distance from the layer-1–layer-2 interface).

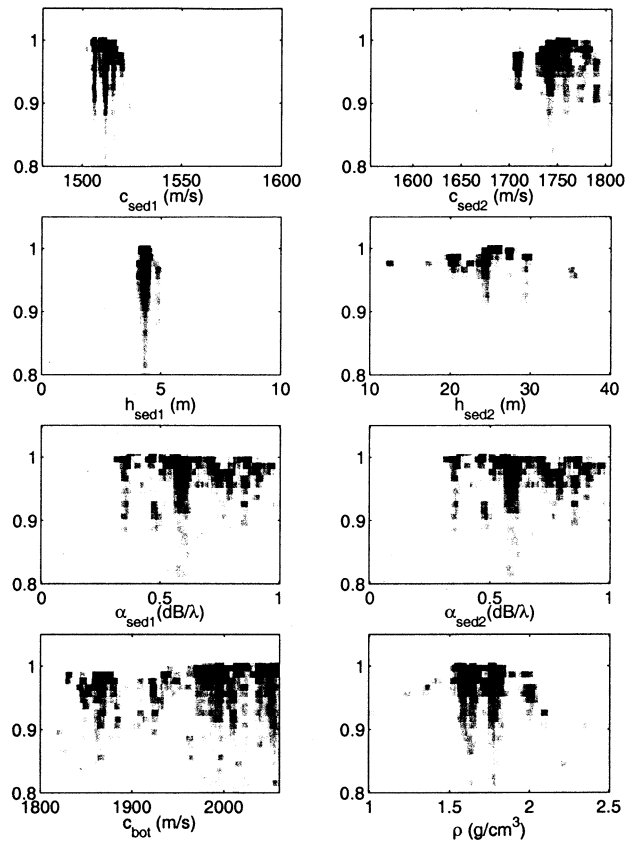

Fig. 4. Cost-function values for TC1 are plotted for the VLA for each of 40 000 environments included in the genetic-algorithm search. Each point on the plot is the correlation value for that particular parameter value. More densely populated areas show where the genetic algorithm is finding higher correlation scores. A peak indicates where a parameter is well determined and a flat distribution indicates little sensitivity. (For this inversion, $h_{\rm sed2}$ was defined from the water–sea-bed interface).

sea-bed properties in tabular form, the top layer and subbottom inverted values are compared directly with ground truth. The middle layers (depth region from about 4 to 25 m) for the ground truth are combined to give a single layer-2 thickness; the sound speed and attenuation in that layer is presented as a range of values. This is the best guess at interpreting the ground-truth sea bed as a two layer over subbottom and appears to be the way the sea bed "looks" to the inversion algorithm. These inversion results for TC1 using the horizontal and vertical arrays are given in Table II.

As Fig. 2 and Table II show, the HLA and VLA results are very similar and both agree well with ground truth. Although the ground truth has a sound speed gradient with several layers, the inversion from a two-layer model approximates that by finding average values.

The relative sensitivities of the two geometries are indicated in the plots of the correlation versus each of the parameter values as shown in Fig. 3 for the HLA and in Fig. 4 for the VLA. These figures indicate almost the same sensitivity structure for the two methods. Note that the HLA results in Fig. 3 have an overall lower correlation value for the best-fit solutions. This lower level of agreement is primarily due to the use of a range-independent propagation model (flat bathymetry) to solve a range-dependent test case.

To further compare inversion results, the workshop participants were asked to provide transmission loss (TL) data as a function of range for a source–receiver geometry *different* than was used for the inversion data. That is, TL was calculated using a source depth of 70 m, receiver depth of 30 m, at frequencies of 80 and 220 Hz. This TL data, using the inverted sea-bed properties from both the HLA and VLA, are shown with the ground truth TL in Fig. 5. The agreement is very good for both the HLA and VLA inversions, especially at closer range where the acoustic measurements were made.

B. TC2

For TC2, the propagation was up-slope and the bathymetry had a slightly higher slope than for TC1. After the initial HLA and VLA inversions, the top layer was found with a thickness close to 0 m and the top sound speed was slightly ambiguous, but fell between 1510 and 1570 m/s. Because the top layer was not being determined well, it was eliminated and the inversion was re-run as a single layer over a half-space. This produced much more well-determined results and the sound speed and layering is shown in Fig. 6. From the figure there is an indication why the two-layer model with the assumption of homogeneous sound speed in the layers could not fit the ground truth well. There is only a slight positive sound speed gradient in the

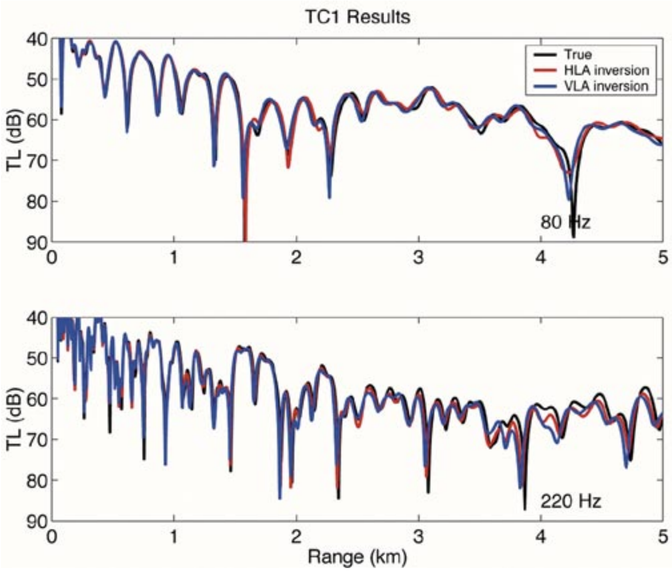

Fig. 5. Transmission loss for TC1 using true sea-bed (black line), HLA (red line), and VLA (blue line) inverted sea-bed values. The source and receiver geometry are different from that used to generate the ground-truth data used in the inversion: source depth was 70 m and receiver depth was 30 m. Top panel is for 80 Hz and lower panel for 220 Hz.

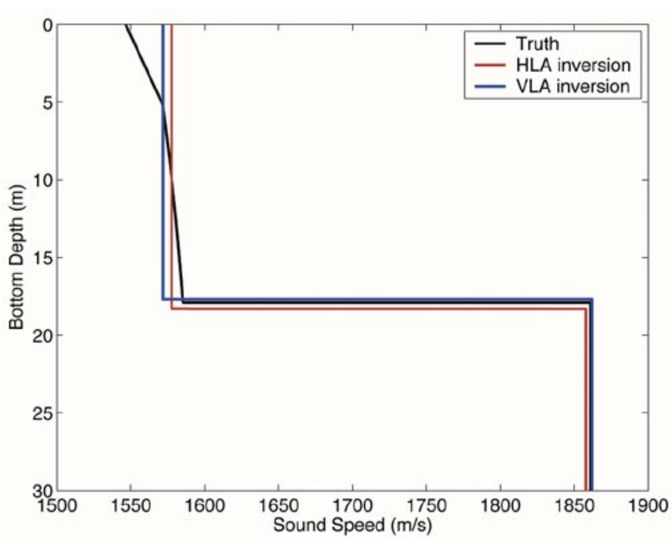

Fig. 6. Sea-bed layering and sound speed from ground truth (black line), HLA (red line), and VLA (blue line) inversions for TC2. The geoacoustic model for inversion was one layer over a subbottom and the ground truth has many layers.

true sea-bed top layer with not enough contrast to appear as two layers. This is best matched using a single homogeneous layer that, in this case, is about 18 m thick. There does not seem to be any advantage to adding a second layer to the inverted geoacoustic model. As was the case for TC1, the ground truth sea bed has many layers and the geoacoustic model used for inversion is more simple. However, the inversion does not seem capable of determining a more complicated geoacoustic structure and the sea bed "looks" like a single layer over a subbottom (i.e., the acoustic information is not sufficient to determine more layers). For comparison of all the inverted parameters, the top layers of the ground-truth sea bed are combined into a single layer (of thickness 17.9 m) and the range of sea-bed values are given in Table III.

TABLE III

Results From Inverting Both Horizontal and Vertical Array Data for TC2. Note, the Geoacoustic Model for Inversion has One Layer Over a Subbottom and the Ground Truth has Many Layers. For Comparison, the Top Layers for the Ground Truth Are Combined Into a Single- Layer Thickness With Sound Speed and Attenuation Presented as a Range of Values. This Is Compared With Inverted Layer-1. The Subbottomis Compared Directly With the Ground Truth

Parameter	HLA	VLA	Truth
Layer-1 thickness: h_{sed1} (m)	18.3	17.7	17.9
Layer-1 speed: c_{sed1} (m/s)	1578	1572	1546–1585
Layer-1 Atten.: α_{sed1} (dB/λ)	0.12	0.17	0.25–0.10
Sub-bot. speed: c_{bot} (m/s)	1858	1862	1861
Sub-bot. Atten.: α_{bot} (dB/λ)	0.23	0.10	0.04
Density: ρ (g/cm^3)	1.3	1.6	1.71–1.98

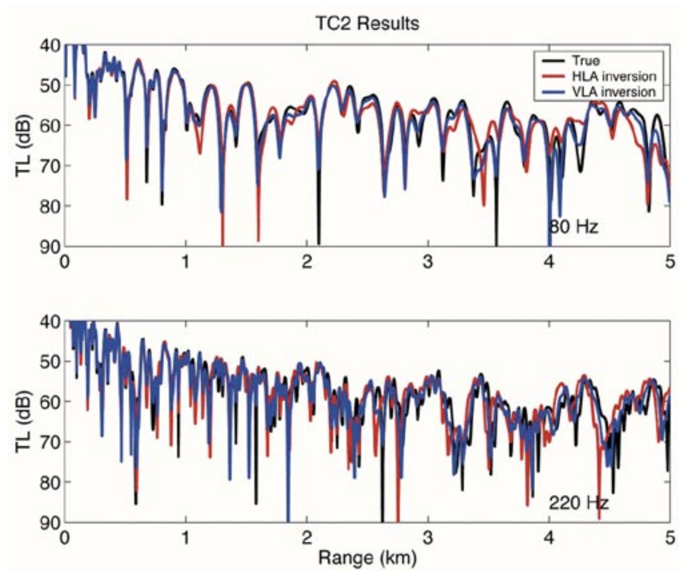

Fig. 7. Transmission loss for TC2 using true sea-bed values (black line), HLA (red line), and VLA (blue line) inverted sea-bed values. The source and receiver geometry are different from that used to generate the ground-truth data used in the inversion: source depth was 70 m and receiver depth was 30 m. Top panel is for 80 Hz and lower panel for 220 Hz.

As was the case for TC1, similar sea-bed characteristics are produced for TC2 using either the HLA or VLA. As previously mentioned, neither the HLA nor the VLA configurations could resolve two layers, but the one-layer model produced reasonably well-determined sea-bed parameter values. And, as before, the HLA used a range-independent model (flat bathymetry) and the VLA included the sloping bathymetry. The TL comparison (with a geometry not used for inversion) is shown in Fig. 7. This TL data is generated using the inverted sea-bed properties from both the HLA and VLA and are shown with the ground-truth TL. As with TC1, the agreement is generally good, especially at closer range where the acoustic measurements were made.

C. TC3

TC3 had a flat bathymetry with a hidden range dependency in the sea bed (see Fig. 1). The data provided to the participants of the workshop was not simulated towed-array data, since the source and array were in fixed locations. For this reason, only the bottom properties under the HLA could be determined at the time of the workshop and, therefore, only sea-bed property results for the first 600 m on the track were reported there.

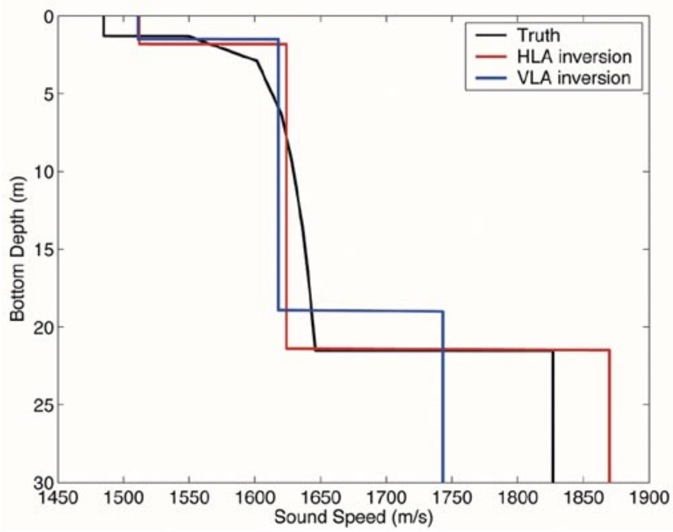

Fig. 8. Sea-bed layering and sound speed from ground truth (black line), HLA (red line), and VLA (blue line) inversions for TC3. The geoacoustic model for inversion was two layers over a subbottom and the ground truth has many layers.

TABLE IV

RESULTS FROM INVERTING BOTH HORIZONTAL AND VERTICAL ARRAY DATA FOR THE FIRST REGION OF TC3. NOTE THAT THE GEOACOUSTIC MODEL FOR INVERSION HAS TWO LAYERS OVER A SUBBOTTOM AND THE GROUND TRUTH HAS MANY LAYERS. LAYER 1 IS COMPARED WITH GROUND TRUTH LAYERS 1–2, LAYER 2 IS COMPARED WITH GROUND TRUTH LAYERS 3–7, AND THE SUBBOTTOM ARE COMPARED DIRECTLY. THE RANGE OF SEA-BED PARAMETER VALUES IS PRESENTED FOR THE GROUND-TRUTH DATA IN THE COMPARISON WITH INVERSION LAYERS 1–2

Parameter	HLA	VLA	Truth
Layer-1 thickness: h_{sed1} (m)	1.8	1.5	2.9
Layer-1 speed: c_{sed1} (m/s)	1512	1511	1485–1602
Layer-1 Atten.: α_{sed1} (dB/λ)	0.7	0.7	0.31–0.85
Layer-2 thickness: h_{sed2} (m)	19.6	17.4	18.6
Layer-2 speed: c_{sed2} (m/s)	1624	1618	1601–1646
Layer-2 Atten.: α_{sed2} (dB/λ)	0.9	0.7	0.85–0.54
Sub-bot. speed: c_{bot} (m/s)	1870	1743	1827
Density: ρ (g/cm^3)	1.6	1.5	1.49–1.98

The ground-truth and inverted sea-bed sound speed and layering for the first region of TC3 (outside the intrusion) is shown in Fig. 8. The figure shows the top two layers of the ground truth (0–2.9 m) sea bed matching up with layer 1 from inversion. Ground-truth layers 3–7 (2.9–21.5 m) match up with inversion layer 2 and inverted subbottom of the geoacoustic model matches up with the ground-truth subbottom. As with TC1 and TC2, the geoacoustic model used for inversion is simpler than the ground truth and the homogeneous layering is an approximation (best fit) to the true sea bed. All the inverted parameters for the first region of TC3 are given in Table IV, where the ground-truth values are compared with the layering interpreted as described.

D. TC3 With Simulated Towed-Array Data

TC3 is perfect for examining the benefits of using a towed array. To show this, data similar to that provided at the workshop was simulated with both the source and array moving along the acoustic track. Using propagation model RAM (as was used for the workshop data), a set of simulations for a towed source and array along TC3 was made using exactly the same frequencies

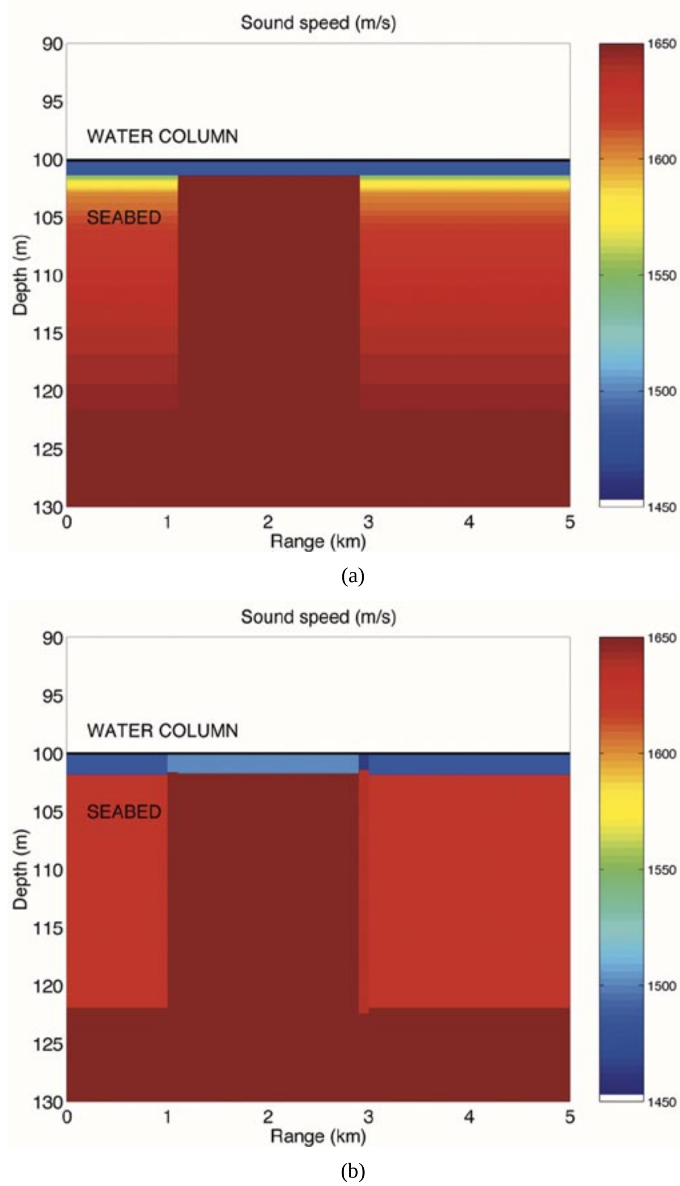

Fig. 9. Sea-bed sound speed as a function of range and depth for (a) TC3 ground truth and (b) inverted using a towed HLA.

and array configuration as for the previous inversions. In principle, data could be taken at regular intervals along the track and inverted. However, with noise-free simulated data, each of these data sets would be identical until the tow begins to enter the region where the bottom properties change. Since the acoustics are exactly the same, the inversion results for each of these data sets will be too. The same inversion procedure as described previously was used for this data. The flat bathymetry in TC3 removed the requirement to use effective parameters and the inversions at each range step were range independent.

The sea-bed sound speed and layering structure is given as a function of both range and depth for the true and inverted sea bed in Fig. 9. The figure indicates the sea-bed properties are well determined in depth and the intrusion is localized at the correct ranges. The inversion values for the sea bed show a rapid change (in range) from one bottom type to another. That is, the local properties are determined as the source and HLA move along the track. The areas around the edges of the intrusion show a slight smearing of the inverted seabed properties, which this is likely due to the acoustic signal spatially sampling the two distinct sea-bed types.

V. Discussion and Conclusion

A comparison was shown here between geoacoustic inversion using horizontal and array data. Horizontal arrays offer many advantages over vertical-array configurations. Horizontal arrays can be towed and are easily deployed from a ship. Towing the array allows for determining range-dependent sea-bed properties while being able to neglect range dependence in the inversion modeling. The required knowledge of the environment is less critical since the modeling is only over the short distance separating a towed source and array. If the horizontal aperture is short, it may provide less information about a wide spread of propagation angles than would a large vertical aperture. However, a typical configuration was used here and there was good sensitivity to the important bottom properties and the overall inversion performance was similar to that using vertical array data. When considering measured data, the uncertainty in the environment (e.g., water column sound speed, slight errors in bathymetry, range dependence in the sea-bed properties) will tend to favor the towed-array geometry over a moored vertical array (especially as the distance between source and vertical-array increases).

For the ITW test cases considered here, the inverted sea-bed properties from the towed array are nearly the same as those from the vertical-array data and both agree well with the known ground truth. The vertical array results are slightly better than the horizontal-array results when inverted sea-bed properties are used to generate transmission-loss data and compared against the true transmission loss. However, for TC3 (flat bathymetry with sea-bed intrusion in the middle of the track), the vertical-array configurations were problematic because the propagation path was over two different sea-bed types resulting in inversions for spatially averaged properties. Using a simulated towed horizontal array, the range-dependent sea-bed properties were well determined along the entire track and, in this case, the towed horizontal array inversion method out-performed the vertical-array inversions.

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