Time-Domain Geoacoustic Inversion of High-Frequency Chirp Signal From a Simple Towed System

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Abstract—An inversion method using a towed system consisting of a source and two receivers is presented. High-frequency chirp signals that have been emitted from the source are received after multiple penetrations and reflections from the shallow water sub-bottom structure and are processed for geoacoustical parameter estimation. The data are processed such that a good resolution and robustness is achieved via matched filtering, which requires information about the source signal. The inversion is formulated as an optimization problem, which maximizes the cost function defined as a normalized correlation between the measured and modeled signals directly in the time domain. The very fast simulated reannealing optimization method is applied to the global search problem. The modeled time signal is obtained using a ray approach. An experiment was carried out in the Mediterranean Sea using a towed source and receiver system. The inversion method is applied to the experimental data and results are found to be consistent with previous frequency-domain analyses using measurements from a towed horizontal array of receivers and measurements on a vertical array.

Index Terms—Geoacoustic inversion, horizontal array, simple towed system, time-domain analysis, very fast simulated reannealing (VFSR).

I. INTRODUCTION

RESEARCH activities on geoacoustic inversions have grown due to the significance of the bottom interaction for shallow-water sound propagation in the ocean. As a result, various techniques to estimate the geoacoustic parameters of the ocean bottom have been developed since direct measurements of the sub-bottom properties are costly and time consuming [1], [2]. Another trend is the growing operation of acoustic equipment including the chirp sub-bottom profiler [3] for the classification and material property estimation of the sediment.

A majority of the inversions in underwater acoustics have been performed using long-range propagation data on a vertical line array (VLA) and produce spatially averaged output [1], [2]. In order to avoid this degradation of resolution, towed horizontal-line-array (HLA) inversion schemes have been proposed

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Digital Object Identifier 10.1109/JOE.2003.816684

and implemented [4], [5]. Most of the analyses with these data are processed in the frequency domain, both narrowband and broadband, except for some that have chosen to deal directly in the time domain [6]–[11]. The inversion is usually formulated as an optimization problem, enabling various optimization techniques to be applied to the inverse problems, such as global optimizations [12], [13] and a hybrid form of global and local search [14], [15]. During the optimizations, the effect of parameter sensitivities or couplings may have to be considered [16], [17]. In an effort to improve the search results, the parameter sensitivities [18] and parameter couplings [19] can be exploited during the optimization process.

Although some areas of the ocean can be characterized as range-independent structures where a simplified parameterization is possible, most locations of the ocean, especially in the shallow waters, show range and azimuth-varying characteristics that require range-dependent parameterizations in geoacoustic inversions. However, the full range-dependent inversions that identify the ocean-bottom structures simultaneously are not tractable so far due to computational burdens in forward modeling. Therefore, simplification of the range dependence into local segments of range-independent sectors is a practical method and implementation via a towed HLA system is a possibility. Siderius *et al.* [5] inverted range-dependent seabed properties by successive range-independent inversions using a towed HLA system working in the frequency domain.

We may require sub-bottom properties with a high spatial resolution in some cases; for example, scattering problems. Holland and Osler [9] reported a high-resolution geoacoustic inversion in shallow water using a joint time- and frequency-domain technique. To achieve high resolution, they used multiple and short aperture measurement techniques. In addition, they exploited multiple independent data to reduce the infamous uniqueness problem that arises in the long-range inversion.

Seong and Park [20] proposed a high-resolution practical inversion method, which was implemented with a relatively simple experimental arrangement using a chirp signal and just two hull-mounted hydrophones. By virtue of a high-resolution characteristic, the chirp signal is suitable for probing the fine-scale structure of the marine sediment. The inversion scheme was based on a direct match of the received and modeled signal in the time domain and the environmental parameters were found through a global optimization using genetic algorithms (GAs). Although more receivers could be used, two receivers were found to be adequate in order to resolve the impedance ambiguity arising for near-normal

Manuscript received July 10, 2002; revised March 12, 2003.

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Fig. 1. Schematic configuration of the hybrid range-dependent inversion using a towed system. A region of interest is segmented and range-independent inversion is applied to each segment successively.

reflections. Their results show a satisfactory match of the sound speed between the inversion and core data.

In this paper, geoacoustic inversion is considered using towed receivers and a broadband chirp signal based on Seong and Park's method [20]. When the receivers are separated only by a few hundred meters from the source, near-field or equivalently steep rays cannot be ignored. In addition, the source signals are linearly frequency modulated (LFM) and their bandwidths are broad (200-850 Hz and 800-1700 Hz). Since global optimization requires numerous runs of forward modeling, ray theory is suitable for practical purposes in terms of calculation time. Although any number of receivers may be employed in the inversion process, two receivers are found to be adequate to resolve the multiple eigenrays. Thus, time-series data from just two receivers out of 256 are utilized. This makes the present method attractive in that a contained system composed of a single vessel equipped with a chirp profiler and two receivers can be easily devised.

As stated previously, various optimization methods have successfully been applied to inversion problems [21]. In general, it is hard to state which method performs superior to others, since the performance is problem specific. In this paper, both GA and very fast simulated reannealing (VFSR) were used. VFSR has been devised to improve the slow convergence rate of simulated annealing (SA), where a flat distribution is used to draw models and the temperature is lowered exponentially. VFSR uses a new probability density to allow exponential cooling schedule, which usually results in faster convergence than SA [22]. The VFSR results showed better performance in terms of the cost function defined in Section II; only its results are presented in this paper.

The present method is applied to the experimental data of MAPEX2000 experiment [23], [25] conducted by the SACLANT Undersea Research Centre, La Spezia, Italy, using a towed system consisting of a chirp signal source and a horizontal line array with 128 receivers. Section II details the overall inversion procedure of parameterization, forward modeling, and global-optimization scheme. They are applied to a synthetic case in Section III for sensitivity analysis. Section IV



Fig. 2. Synthetic signal constructed by the forward model. (a) Arrival structure of the eigenrays. (b) Impulse response. (c) Synthetic matched-filtered signal. (d) Noise-added matched filtered synthetic signal (SNR = 3 dB).

describes the experiment and numerical results from processing the data, with a concluding remark in Section V.

II. INVERSION SCHEME

A. Inversion Overview

The inversion method of this paper is described in terms of 1) parameterization, 2) forward modeling, and 3) optimization scheme.

Parameter	Value	
Water sound speed	1500 m/s	
Source depth	57 m	
Receiver range	310 m	
Receiver depth	60 m	
Bottom depth	100 m	
Sediment 1 speed	1470 m/s	
Sediment 1 density	1.2 g/cm ³	
Sediment 1 attenuation	0.1 dB/ λ	
Sediment 1 thickness	5 m	
Sediment 2 speed	1550 m/s	
Sediment 2 density	1.3 g/cm ³	
Sediment 2 attenuation	0.1 dB/ λ	
Sediment 2 thickness	20 m	
Sub-bottom speed	1650 m/s	
Sub-bottom density	1.35 g/cm ³	

The appropriate parameterizations depend mainly on the experimental sites. Since most locations of the ocean, especially in shallow waters, show range and azimuth-varying characteristics, simple range-independent inversions using the long-range propagation data will render range-averaged parameter values of the region. If the region of interest is segmented as shown in Fig. 1 and the range of each segment is moderately short, the range dependency of a segment can be minimized or hopefully eliminated. By successively applying range-independent inversions to the data sampled by a towed system, the bottom properties of the whole region can be determined distinctively.

The range of a segment should be chosen carefully, considering both the efficiency of the experimental procedure and the accuracy of the numerical-inversion procedure. The distance between the source and receiver should be short enough to assure the range independency of the bottom properties and also to reduce the degradations of geoacoustic estimates that can be caused due to the ocean sound-speed variability. At the same time, the offset between the two receivers should be large enough to avoid a velocity-depth ambiguity in the analysis based on travel times [24] and small enough to do fast modeling. Considering the above limitations, an order of hundreds of meters of distance between the source and receiver may be reasonable for the inversion.

The geoacoustic model of a segment is simple relative to the range-dependent models. The seabed consists of a number of parallel sedimentary layers and a sub-bottom. The geoacoustic parameters including the sound speed, attenuation, and density of each sediment layer and the sub-bottom are homogeneous in range. A two-layered sediment model is used in this paper, based on the analysis of the arrival time structure of the signal. The attenuation is included only during the numerical simulation in Section III for the sensitivity analysis. The attenuation does not



Fig. 3. Cost-function evaluation for the sensitivity study. In each plot, the true value is shown by a vertical dashed line, and the rest of the parameters are fixed at their true values. Note the ordinate scale difference in the densities and attenuations. The solid lines are for high-frequency chirp (800–1700 Hz), and the dotted lines are for low-frequency chirp (200–850 Hz).

affect the wavefield significantly when the propagation distance is short, as in our towed system. In addition, since the main focus of the present research is on time-domain inversion using broad-band signals, the attenuation, inherently being a function of frequency, will be ignored in the experimental data inversions in Section IV.

The forward model is chosen from considerations such as the experimental conditions and the source-signal characteristics. We chose the ray method for our forward model due to the short distance between the source and receiver in the towed system and also due to the high-frequency LFM signals (800–1700 Hz) used in the experiment. As the frequency increases, which is required for the high spatial resolution, the ray approach becomes more attractive than frequency domain calculations in terms of computation time. Fig. 2 schematically shows the simple procedure of the forward modeling. First, the eigenrays are identified for a given environment (shown in Table I) and numbered in arrival-time sequence, as shown in Fig. 2(a). Then, corresponding amplitudes and time delays, i.e., impulse responses, are calculated for each ray, as in Fig. 2(b). Finally, the synthetic signal is constructed via convolution of the source signal and the impulse



Fig. 4. Scatter plots of the cost-function value with respect to corresponding parameter searched during global optimization—numerical simulation. In each plot, the true value is shown by a vertical dashed line.

response and then matched filtered [Fig. 2(c)]. For the inversion of numerically simulated data, white noise [signal-to-noise ratio (SNR) = 3 dB] is added as shown in Fig. 2(d). Since the noise is added prior to match filtering, most of it vanishes after it is matched filtered, as shown in the figure. Details of the forward model will be elaborated later in this section.

The VFSR is a modified SA and has been found to be very useful in several geophysical applications [21]. The performance of the optimization may be affected by the nature of the parameter space. A simple way to improve the performance is to reduce the number of parameters by simplifying the environmental models or ignoring insensitive parameters [25]. The ray-based inversions have been established as multistep approaches in which the bottom parameters are confined to one layer and inverted successively layer by layer [10], [20]. Although the layer-by-layer scheme seems to be suitable for the time-domain inversion, it is hard to apply in the cases where unresolved signals are present.

Direct and surface reflected signals (ray 1 and ray 4 in Fig. 2) usually have large amplitudes, but they contain only geometric information, such as the source and receiver positions and thus are not useful for the inversion of bottom properties. If the geometry and bottom properties are inverted simultaneously, the search process of geometrical parameters will dominate over bottom parameters. However, when the bottom properties are inverted using *a priori* geometry, incorrect geometry information,

TABLE II Search Intervals of the Geoacoustic Parameters in Experimental Data Inversions

Parameter	Search minimum	Search maximum
Sediment 1 speed C_{sed1} (m/s)	1450	1700
Sediment 1 thickness h_{sed1} (m)	1	30
Sediment 2 speed $C_{sed 2}$ (m/s)	1500	1800
Sediment 2 thickness h_{sed2} (m)	1	30
Sub-bottom speed C_{bot} (m/s)	Sediment 2 speed	Sediment 2 speed +250
Density $\rho(g/cm^3)$	1	2
Sediment 2 speed C_{sed2} (m/s) Sediment 2 thickness h_{sed2} (m) Sub-bottom speed C_{bot} (m/s) Density ρ (g/cm ³)	1500 1 Sediment 2 speed	1800 30 Sediment 2 speed +250 2

TABLE III Search Intervals of the Geometrical Parameters Around *a Priori* Values in Experimental Data Inversions

Parameter	Search interval	
Source depth	±1m	
Receiver range	±15m	
Receiver depth	± 10m	
Bottom depth	±1m	

possibly due to experimental errors, may degrade the estimates. Therefore, we adopt a two-step approach for the inversion, similar to the work done by Siderius *et al.* [5]. In the first step, both the geometric and geoacoustic parameters are searched for at the same time. Since the search for geometric parameters usually converges quickly, search continues concentrating only on the bottom properties with the geometry fixed after the initial short inversion. Using this two-step method, we can reduce the number of parameters to assure stable estimates for the geoacoustic parameters as well as eliminate the dominance of the direct and surface-reflected signals.

The cost function to be maximized for the inversion is defined by

$$C = \frac{1}{N_R} \sum_{i=1}^{N_R} \frac{\left| \sum_{k=1}^{\infty} w(k) p_i(k) q_i(k) \right|}{\sqrt{\sum_{k=1}^{\infty} w(k) p_i(k)^2} \sqrt{\sum_{k=1}^{\infty} w(k) q_i(k)^2}}$$
(1)

where N_R is the number of receivers, k represents time samples, w is a window, p and q represents measured and simulated discrete time signals, respectively. Note that since the trigger time is known, alignment of measured and simulated signals is not necessary and is taken care of automatically in the modeling as travel time of the signal. Two receivers ($N_R = 2$) are used in this paper. By normalizing the cost function as in (1), absolute strength of the source signal need not be identified. The cost function will have a maximum value of 1 when two signals are matched exactly in relative amplitude. Since it is common to truncate the time signal as to include only the meaningful parts in inversions, the truncation is realized through a rectangular window w.



Fig. 5. Brief description of time-domain inversion scheme using HF 08:06:51: (a) Raw data recorded by receiver1 (top) and receiver2 (bottom). (b) Matched filtered data. (c) Modeled data using inverted parameters. (d) Comparison of the envelopes of matched filtered data (solid line) and modeled data (dotted line). Note the difference of starting times between top and bottom signals.

TABLE IV COMPARISON OF HIGHEST CORRELATIONS PARAMETERS FOR HF 08:06:51 AND LF 08:07:00

Parameter	HF 08:06:51	LF 08:07:00
Sediment 1 speed C_{sed1} (m/s)	1502	1489
Sediment 1 thickness h_{sed1} (m)	10.3	9.4
Sediment 2 speed C_{sed2} (m/s)	1638	1691
Sediment 2 thickness h_{sed2} (m)	28.3	24.4
Sub-bottom speed C_{bot} (m/s)	1712	1725
Density $\rho(g/cm^3)$	1.15	1.10
Cost function	0.95	0.95

B. Forward Modeling Based on Ray Theory

The acoustic data received at a receiver consist of coherent signals from distinct ray paths. Generally, the discrete signal p can be constructed from the following convolution:

p

$$=g*s \tag{2}$$



Fig. 6. Scatter plots of the cost function value with respect to corresponding parameter searched during global optimization-inversion of HF 08:06:51 data. The arrow indicates the parameter value with the best fit.

where g is the impulse response and s is the source signal. The impulse response is a function of the amplitudes and travel times. To calculate the impulse response, we make the following assumptions:

- 1) The medium is stratified, not necessarily horizontally, and the acoustical properties in each layer are homogeneous.
- The roughness of layer boundaries is small enough to be neglected.
- There is no deformation of the signal after reflections or transmissions.
- 4) The source is omnidirectional.

Assume a ray emanating from the source with grazing angle θ_i . When the ray reaches an interface, call it a branch point, it reflects up and transmits down with changes in both the propagation angles and amplitudes. If we ignore the geometrical spreading for the time being and assume a planar interface, the propagation angles and the amplitudes are easily calculated, even for a slanted interface [26]. The branch points are tracked and stored until the ray reaches the receiver range. The ray is determined as an eigenray if it arrives at the receiver position within a predetermined error bound. Finally, the resulting amplitude of the eigenray is calculated by

$$A_{\text{eigen}} = C_s \prod_{i=1}^{N_B} A_i \tag{3}$$

where N_B is the number of branches and C_s is the overall geometrical spreading loss factor. The overall geometrical spreading loss factor is conveniently approximated as equivalent spherical spreading (1 is the total length traversed by the ray). Finally, the impulse response becomes

$$q(k) = \sum_{i=1}^{N_E} A^i_{\text{eigen}} \delta(k - \tau_i)$$
(4)

where δ is the Dirac delta function, N_E is the number of eigenrays, and τ is the travel time. The travel time and the total length traversed by an eigenray are easily calculated from the stored information of branch points.

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III. INVERSION—NUMERICAL SIMULATION

Before applying the inversion scheme to the experimental data, we performed preliminary inversions using simulated data. The environment is the same as that used for generating the time signals in Fig. 2 and the parameters for the simulation study are given in Table I. All simulations are performed with SNR = 3 dB. Notice that the sound speed in the sediment is lower than in the water, representing the site where the first part of the data were collected during the experiment. In addition to the first receiver, a second receiver is placed 128 m away from the first receiver at the same depth of 60 m. The simulation study has two purposes. The first is to gain insights about the sensitivity



Fig. 7. Two-dimensional scatter plots of the cost function value with respect to selected parameters searched during global optimization-inversion of HF 08:06:51 data.

of the geoacoustic parameters. Since there are numerous results on matched-field inversion with vertical line arrays, a relatively good understanding of the sensitivity exists. However, less information is known regarding the time-domain inversions using the towed system consisting of a small number of receivers. The second purpose is to validate the proposed inversion scheme with known parameters.

The first method to estimate sensitivity is to investigate the behavior of the cost function as a function of selected parameter with other parameters fixed at their reference values. This kind of sensitivity test is a common practice in geoacoustic inversion. Although the sensitivity estimates using one parameter may show biased results due to parameter couplings [27], it will be meaningful to compare the sensitivity for our time-domain inversion with that of other matched field inversions.

Fig. 3 shows the sensitivity curves of the bottom parameters using chirp signals of two different frequency bands. The solid lines are for a chirp with 800–1700 Hz bandwidth, whereas the dotted lines are for 200–850 Hz banded-chirp signals. It should be noted that the less-sensitive parameters have different ordinate scales. From Fig. 3, it can be shown that the overall sensitivity of the high-frequency signal is higher than the low frequency, due probably to the increased resolution. The proposed inversion has a high sensitivity to sound speeds and layer thicknesses for both frequencies. On the other hand, there is a weak sensitivity to the densities and the attenuations. It is noted that the results in Fig. 3 show similar behavior

to those of previous research in matched field inversion, especially to the results of Siderius *et al.* [5] obtained using a one-layer model.

Next, we performed a full inversion for the bottom parameters using the same reference high-frequency signal (800-1700 Hz). The parameter intervals for the simulation are 1400–1700 m/s for sediment 1 sound speed (C_{sed1}) , 1500–1800 m/s for sediment 2 (C_{sed2}) and bottom sound speed ($C_{\rm bot}$), 0–30 m for sediment-layer thicknesses ($h_{\rm sed1}$ and $h_{\rm sed2}$), and 1–2 g/cm³ for densities ($\rho_{\rm sed1}$, $\rho_{\rm sed2}$, and $\rho_{\rm bot}$). The inversion results are presented in Fig. 4. Although one-dimensional (1-D) marginal a posteriori probability [12], [21] display of the results is a common practice, we plotted all 15000 cost-function values with respect to the corresponding parameter values visited during the VFSR search without any post processing. By doing so, we can attain information about the optimizer (VFSR) such as its behavior related with the parameter sensitivity and sampled parameter space. From Fig. 4, we can see that the search converges to true values as the temperature of the VFSR is lowered. However, the convergence rates or patterns differ from each other. Related with the first sensitivity study, it can be shown that sensitive parameters are resolved better or sampled more densely than the insensitive ones. Therefore, it seems to be possible to directly infer the sensitivity of each parameter from the scatter plots in Fig. 4. It is also noted that the envelopes of the plots in Fig. 4 resemble the corresponding sensitivity curves in Fig. 3.



Fig. 8. Scatter plots of the cost-function value with respect to corresponding parameter searched during global optimization–inversion of HF 08:38:51 data. The arrow indicates the parameter value with the best fit.

The most probable solution of the inversion problem is the set of parameters yielding highest cost-function value or correlation between the measured and modeled data. The highest correlated parameters of the inversion simulation are: $C_{sed1} = 1462$ m/s, $C_{\text{sed2}} = 1548 \text{ m/s}, C_{\text{bot}} = 1635 \text{ m/s}, h_{\text{sed1}} = 4.8 \text{ m}, h_{\text{sed2}} = 19.6 \text{ m}, \rho_{\text{sed1}} = 1.2 \text{ g/cm}^3, \rho_{\text{sed2}} = 1.4 \text{ g/cm}^3, \text{ and } \rho_{\text{bot}} = 1.4 \text{ g/cm}^3$. The matches between true (Table I) and estimated parameters are consistent with the sensitivity of corresponding parameters. Highly sensitive parameters are estimated better than the insensitive ones. It is remarkable that the sound speed and the thickness of the sediment 1 are well determined even though the amplitude of the signal reflected from the sediment 1 is low (ray 2 in Fig. 2). However, the little contribution of the unresolved signal reflected from the sediment 1 to the inversion results in the low sensitivity or the broadening in scattered plots in Fig. 4 relative to the parameters of sediment 2. Therefore, it can be said that the resolution as well as amplitude of the signal has high correlation with the sensitivity of the parameters in the time-domain inversion. We also performed the same inversion using low-frequency signals and obtained similar results, which are not shown.

IV. INVERSION-EXPERIMENTAL DATA

The MAPEX2000 experiments were conducted by the SACLANT Undersea Research Centre on the Malta Plateau (between Italy and Malta) from February 22 to March 27, 2000. In the experiments, a towed system consisting of a source and a horizontal line arrays with 128 receivers was used. The flextensional source mounted in a towed fish emitted a sequence of 1-s linear frequency-modulated sweeps (pings), which have the frequency bands of 200-850 and 800-1700 Hz. The sweeps are denoted as LF for low frequency and HF for high frequency, respectively. The distance between the source and the first receiver was approximately 300 m and the spacing between adjacent receivers was 2 m. As described previously, data set taken from various combinations of receivers are possible. Inversion results from the time-series data of a single receiver have proved to be quite ambiguous, whereas data set from two receivers improved the inversion results with much-reduced ambiguity. Utilizing data from three receivers improved the results by an unnoticeable amount. In this paper, the time-series data from two receivers separated 128 m are



Fig. 9. Two-dimensional scatter plots of the cost-function value with respect to selected parameters searched during global optimization-inversion of HF 08:38:51 data.

used (source-receiver ranges 300 and 428 m). The data were sampled March 27. Sound-speed profiles were measured during the experiments. The typical profiles were slightly upward refracting and the overall difference between the top and bottom of a water column was less than 4 m/s. Therefore, the sound speed of the water column can be assumed to be homogeneous. The details of the experiments are described in Siderius *et al.* [5].

A total of 18 pings are considered: nine HF pings recorded from 08:06:51 to 09:10:51 UTC and nine LF pings recorded from 08:07:00 to 09:11:00 UTC. The time interval between adjacent pings of the same frequency band is 8 min, which results in covering about 9 km along the track for each frequency. Since the LF pings were transmitted immediately after the HF pings, the regions that are covered by these two adjacent transmissions can be considered as essentially the same. The received time data will be used as reference signals after matched filtering.

In order to assure convergence, three independent inversions totaling 30 000 forward calculations are carried out for each ping. The geoacoustic parameters and the search intervals are given in Table II. These are almost the same as those used in numerical simulation of Section III, except that the sub-bottom is fast and its density is assumed to be homogeneous due to weak sensitivity. The search bounds for the geometrical parameters are given in Table III based on *a priori* information or measurements [5].

Before discussing the inversion results, we describe the time-domain inversion scheme briefly again, using the real data shown in Fig. 5. The signals are recorded by two receivers [Fig. 5(a)] and matched filtered [Fig. 5(b)]. The modeled signals using the estimated parameters via global searches are shown in Fig. 5(c). Finally, the envelopes of both the measured (solid line) and modeled (dotted line) signals seem to be matched well as in Fig. 5(d).

Individual sector results are first reviewed for consistency. Two inversions using HF 08:06:51 and LF 08:07:00 are compared in terms of best parameters in Table IV. The estimates show good agreement, which is consistent when considering that the spatial distance between the two pings is short.

As for the convergence and accuracy of the inversion results, Fig. 6 shows the scatter plots of the inversion, which was carried out using HF 08:06:51. For each parameter the value of the cost function is plotted for all forward model realizations during the VFSR process. The result shows a distinct thin soft layer. However, the second layer is not resolved. The inversion using LF 08:07:00 showed similar results, which are not shown in the paper. There could be two possibilities for the cause of this uncertainty in the second sedimentary layer. The first is due to the over-parameterization, in which case one-layered model should have been adopted to describe the seabed. The second possibility is due to parameter couplings. Since the scatter plot is a 1-D projection of the multidimensional search space, it could be unresolved if the parameters are strongly correlated. In order to clarify the problem, two-dimensional (2-D) projections of the cost function values are plotted as in Fig. 7. They are constructed by selecting the highest cost



Fig. 10. Inversion results using nine HF data transmitted from 08:06:51 UTC (right of the figure) to 09:10:51 UTC (left of figure) and nine LF data from 08:07:00 UTC (right of the figure) to 09:11:00 UTC (left of the figure). (a) HF inversions. (b) LF inversions. (c) Previous work by Siderius *et al.* [5] using LF signals processed in the frequency domain.

function values, sampled during the whole VFSR search, which falls into the bin corresponding to the parameters shown on the axes. A similar approach was followed by Jaschke and Chapman [8]. This 2-D plot implicitly shows the correlation between various combinations of the parameters. Relatively little correlation between the sound speed and layer thickness of sediment 2 is found. This suggests that over-parameterization occurred in this region. Other correlations are in accordance with previously known coupling phenomena, especially the strong correlation of sediment layer thickness and sound speed in the first layer. Since it is common to observe strong coupling between sound speed and sediment depth [27], the absence of this correlation could indicate that the layer is not important. To prove the argument of the previous discussion, Fig. 8 shows the scatter plots of the inversion with other data, HF 08:38:51, and Fig. 9 shows the corresponding 2-D plots. From Figs. 8 and 9, we can observe different features from those of Figs. 6 and 7. It is noted that all the layers are fully determined in Fig. 8. However, parameters pertaining to the first layer show lower cost-function values than those of Fig. 6, although the correlation between sound speed and thickness of the first layer is similar for both Figs. 7 and 9. This can be explained as a global search problem, where for the latter data case with more valid parameters for which to invert, convergence will be slower.

In conclusion, range-dependent inversion results of the bottom properties for the nine HF pings and the nine LF pings are shown in Fig. 10, compared with the previous work by Siderius *et al.* [5] using LF signals. The figure shows the sound speed and the layer structure. Since the towed system covers about 500 meters per one ping, the remaining regions are assumed to be the same. The three plots show consistent layering and sound-speed variations.

V. CONCLUSION

Predicting bottom properties is important for various acoustic applications in shallow waters due to the significance of the bottom interaction. This paper describes a feasible geoacoustic inversion method using a simple towed system consisting of a source and two hydrophones.

The inversion was performed in the time domain using broadband signals (two frequency bands between 200–1700 Hz) recorded by two towed receivers. Simplification of the range dependence into local segments of range-independent sectors was implemented to reduce the computational burdens due to complicated parameterization of range-dependent inversions. The propagation of linear frequency-modulated chirp signals, suitable for probing the fine-scale structure of the marine sediment, was modeled using a ray-theoretic method. The cost function was defined as an incoherent sum of normalized correlation values between received and modeled signals. Then, a series of global searches was performed using VFSR to find the optimum parameters.

The numerical simulation study for sensitivity tests using synthetic signals showed similar results of the previously reported matched field inversion using a towed horizontal line array. It is noted that the sound speeds and layer thicknesses were resolved much better than the densities and attenuations; this should be accepted as a main characteristic of the geoacoustic inversion. The inversion result using synthetic data validated the proposed inversion method.

The present method was applied to the experimental data of MAPEX2000. Eighteen pings using nine HF (800–1700 Hz) and nine LF (200–850 Hz) signals were inverted successively. 1-D and 2-D scatter plots of cost function showed the sensitivity and correlations of various parameters. From the inversions with experimental data, we have found that the time domain geoa-coustic inversion using a relatively simple experimental setup and high-frequency chirp data will yield reliable and high-resolution results.

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