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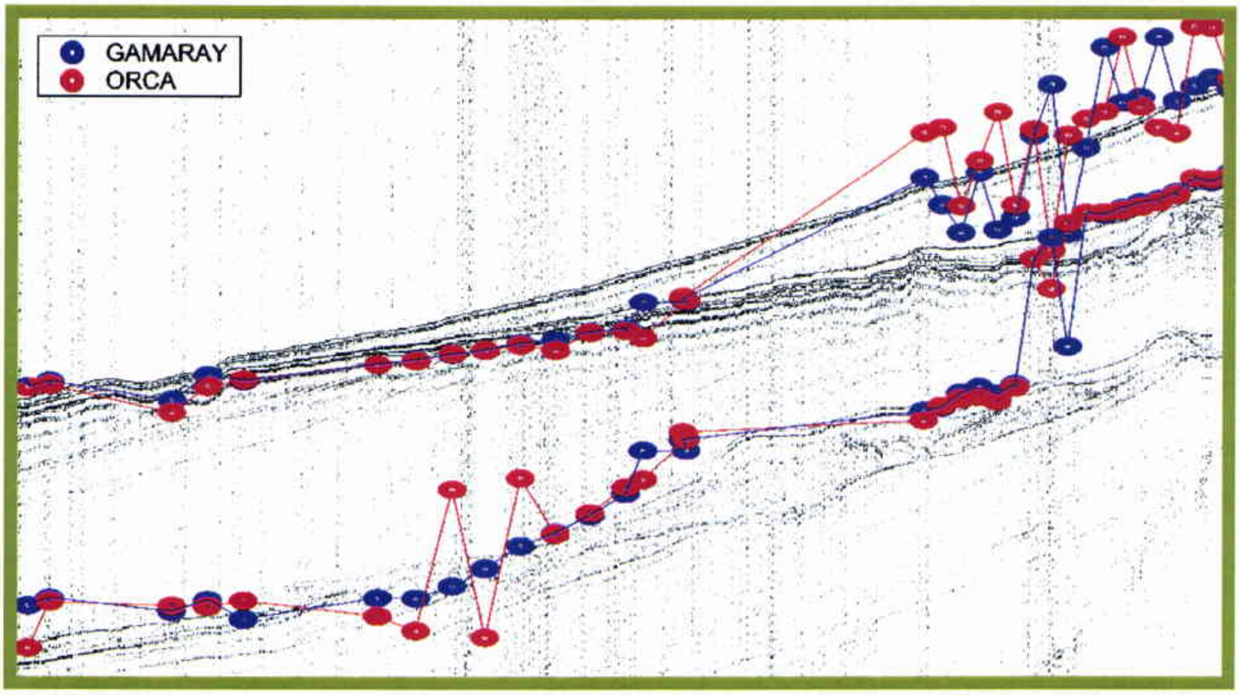
The characterization of a range-dependent environment using towed horizontal array data from the MAPEX 2000 experiment



Mark Fallat, Peter L. Nielsen
and Martin Siderius

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NORTH ATLANTIC TREATY ORGANIZATION   ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD

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Jan L. Spoelstra
Director

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Executive Summary:

It is a commonly accepted fact that in the littoral environment bottom properties have a significant influence on the acoustic propagation. It is both very difficult and very important to acquire accurate estimates of the environmental properties. Currently, environmental databases are often the only resource available to obtain estimates of the various environmental properties. Unfortunately, existing databases generally have neither the spatial resolution nor the necessary accuracy to be effective in most situations. Therefore, it is paramount to devise a method of obtaining environmental properties for littoral environments anywhere in the world. Geoacoustic inversion techniques can provide accurate estimates of the environmental properties for most littoral situations. The drawback is that, to date, most geoacoustic inversion experiments have made use of data recorded at a vertical array of sensors which, from an operational stand point, is not a very feasible configuration. For this reason, a new "through-the-sensor" approach that makes use of current or future operational systems must be developed.

In this report, a new technique of geoacoustic inversion which attempts to make use of a "through-the-sensor" approach, is developed and applied to experimental data from the Mediterranean Sea. The technique is validated first on synthetic data which was designed to closely simulate the acoustic propagation through the real environment. The actual inversion results are compared to various forms of ground truth data and to data recorded during the same experiment but on a different system. In both cases the results are in good agreement with the other data sets.

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The characterization of a range-dependent environment using towed horizontal array data from the MAPEX 2000 experiment.

Mark Fallat, Peter L. Nielsen and Martin Siderius

Abstract: The characterization of ocean environments using geoacoustic inversion techniques has received a lot of attention in recent years. Generally, the inversions are carried out on data recorded at a vertical array of sensors which often produces good results but, from an operational stand point, can be difficult to accommodate. This paper describes the characterization of an ocean environment using data recorded on a horizontal array of sensors. Data from the MAPEX 2000 experiment, conducted in the Mediterranean Sea in 2000, are used to determine seabed parameters for a range-dependent environment. A "*proof-of-concept*" is provided using synthetic data.

Keywords: Geoacoustic Inversion ∘ Horizontal Towed Array ∘ Strait of Sicily ∘ Malta Plateau ∘ Matched Field Processing ∘ Genetic Algorithms

Contents

1 Introduction

In recent years, considerable effort has been given to using geoacoustic inversion techniques to estimate environmental parameters from recorded acoustic data. These techniques have provided a viable solution to measuring the *in situ* environmental parameters from acoustic data. Currently, the standard approach for geoacoustic inversion is matched field processing (MFP). MFP is a forward modeling approach which attempts to minimize some measure of the mismatch between measured and synthetically generated (modeled) acoustic data.

Generally, geoacoustic inversion experiments have made use of data recorded at a vertical array (VA) of sensors. This configuration provides many advantages including the ability to distinguish between sound arriving at different vertical angles. Also, if the VA is moored then large regions can be covered by simply towing a source around the area of interest. However, this technique is not without limitations. As the range between the source and receivers increases, the influence of environmental variability can reduce the accuracy of the estimates. Finally, from an experimental point of view, VA's can be difficult and expensive to deploy at multiple sites.

An alternative to using a VA is to deploy a towed horizontal array (HA) of sensors. Using a towed HA has several benefits. First, the source-receiver separation is constant and is often small (in shallow water it will be on the order of a few water depths). This has several advantages, including the fact that the properties along the propagation path can generally be assumed as range-independent and variability in the water column is generally considered to be negligible. Also, because both the array and source are towed, large regions can be analyzed in a short amount of time. Lastly, HA's are quite simple and inexpensive to deploy at multiple sites within an experimental area. A disadvantage to inversion using HA data is that the sensors generally span a very small portion of the water column (on the order of a few meters) therefore the length of the array determines the angles at which acoustic energy is received. Therefore, for some experimental configurations, the HA may have to be very long or towed a great distance behind the source which can be prohibitive because of both cost and logistical considerations.

In the past, there have been a few studies that attempted geoacoustic inversion with towed HA data [1, 2, 3]. These studies met with varying levels of success but several of the limitations in techniques and tools have now been overcome.

This study is intended to explore a new approach to the characterization of an environment using geoacoustic inversion. The most recent work by Siderius et al. [3] is a precursor to the work in this paper. In that paper, they looked at a limited set of data from the MAPEX 2000 experiment and carried out geoacoustic inversions to characterize the environment. Here the work is taken another step forward, a series of inversions are carried out at multiple points along an experimental track. The series of inversions or "*snap-shots*", are then used to build a full range-dependent model of the environment.

In order to confirm the feasibility of this technique a synthetic study, designed to represent the important features of MAPEX 2000 experimental area, was performed. This analysis was then used to help devise the appropriate strategy for the inversion of the recorded MAPEX 2000 data.

The paper is organized into the following sections, Sec. 2 provides a brief overview of the inversion algorithm and the propagation models that were used. Sec. 3 briefly describes the MAPEX 2000 experiment. The overview of the synthetic study is given in Sec. 4, and Sec. 5 provides the summary of inversion of the MAPEX 2000 data. An evaluation of the range-dependent environmental properties is given in Sec. 6 and finally, the conclusions of the work are give in Sec. 7.

2

Inversion Algorithm and Propagation Models

Geoacoustic inversion techniques have provided scientists with the ability to accurately determine *in situ* environmental properties from measurements of ocean acoustic fields. In recent years, MFP has become the standard technique for geoacoustic inversion. MFP is a forward modeling approach where the goal is to minimize some degree of mismatch between measured and modeled acoustic fields. The problem can essentially be defined as a global optimization. This global optimization can be extremely difficult, the parameter space is generally quite large and very non-linear. Also, parameter correlations exists which can produce sub-optimum solutions. Finally, the parameters have varying levels of influence on the mismatch (i.e., one parameter may cause dramatic changes in the mismatch while another parameter may produce no appreciable change). It is therefore critical to choose an effective search algorithm for the problem.

In this study the genetic algorithms package SAGA [4] is used. Genetic algorithms attempt to find an optimal solution using procedures that are based on analogies with the process of biological evolution [5]. The technique offers a practical solution to most (if not all) of the issues associated with inversion using MFP. It has been successfully applied to various geoacoustic inverse problems [3, 6, 7] and is widely accepted as being one of the standard inversion algorithms.

Once an appropriate inversion algorithm has been chosen, a forward propagation model must be selected. In this study two different propagation models were used for the inversions. The inversions were carried out using the normal mode model ORCA [8] and the ray theory model GAMARAY [9, 10]. ORCA is a layered propagation model that includes the continuous spectrum and can provide accurate estimates of the acoustic field for most range-independent environments. GAMARAY is a ray theory model that is extremely efficient and allows for multiple layers in the sub-bottom.

3

MAPEX 2000 Experiment

In March 2000, SACLANT Undersea Research Centre conducted the MAPEX 2000 experiment in the Strait of Sicily, Mediterranean Sea (Fig. 1). One of the purposes of the experiment was to test the effectiveness of inversion using data recorded on a HA and to compare those results to inversion results from VA data. The area was chosen for several reasons one of which was that numerous other experiments have been conducted in the region. This provided a considerable amount of ground truth data and complementary acoustic data inversion results.

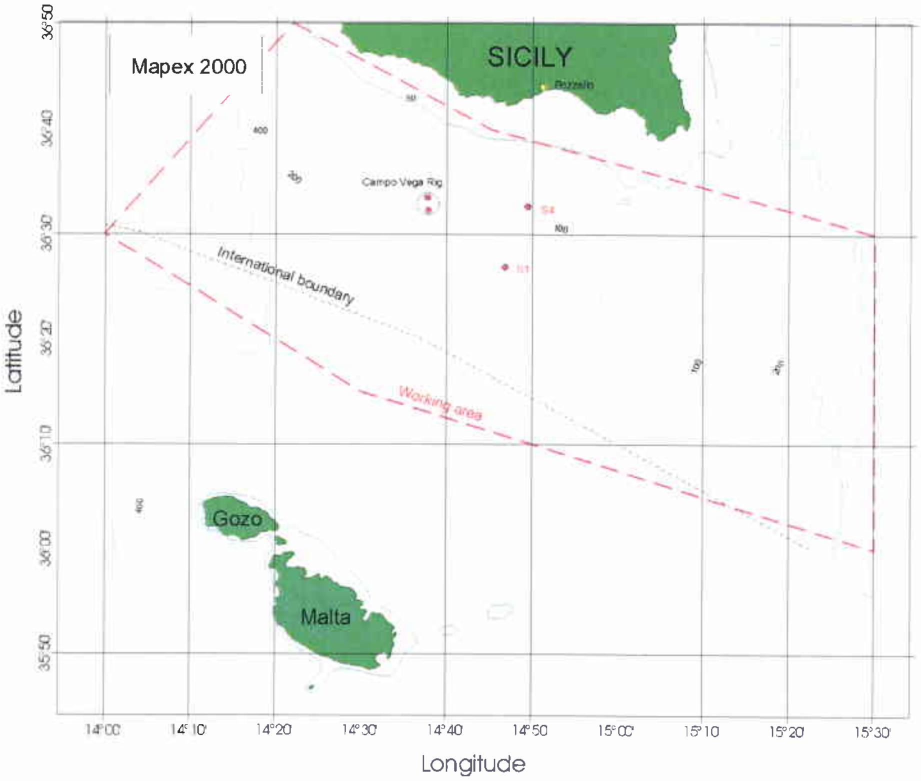

Figure 1 The MAPEX 2000 experimental site. The ship track went from S4 through S1.

During the experiment various data were collected. The acoustic data consisted of both linear frequency modulated (LFM) and multi-tone (MT) signals transmitted from flextensional sources. The data considered in this study were LFM signals from 250Hz - 800Hz recorded on March 7^{th}. The recorded acoustic pressures were converted into the frequency domain using the Fast Fourier Transform (FFT). In an effort to reduce computation time during the inversions, frequency bands in 50Hz increments were used.

The acoustic data were calibrated using a measured source spectrum. This source spectrum was measured two days before the experiment started. The measurement was made using a reference hydrophone that was placed in the water very close to the source (on the order of a few meters in water that was $\approx$ 100m deep).

Environmental data were provided from a variety of different sources. Sound speed profiles were obtained using both conductivity, temperature and depth (CTD) and expendable bathythermograph (XBT) sensors. These measurements were taken before, during and after the acoustic data were recorded. Bathymetry measurements at the time of each acoustic ping were provided by a mulitbeam echosounder. Also, pressure sensors at the head and tail of the HA provided estimates of the depth of the HA. The depth of the source was also measured using a pressure sensor and all of the depth values were inserted into the acoustic data files by the data acquisition system.

Earlier experiments conducted in the area provided core data and seismic profiles. Fig. 2 is a high-resolution seismic profile from the SCARAB 98 experiment. In Fig. 2 *Twtt* is the "Two Way Travel Time". The profile shows a smoothly varying environment with a well defined layering structure. The available core data were not used as ground truth but were used to help determine reasonable search bounds for some of the properties. For a more detailed description of the MAPEX 2000 experiment the reader is referred to [3].

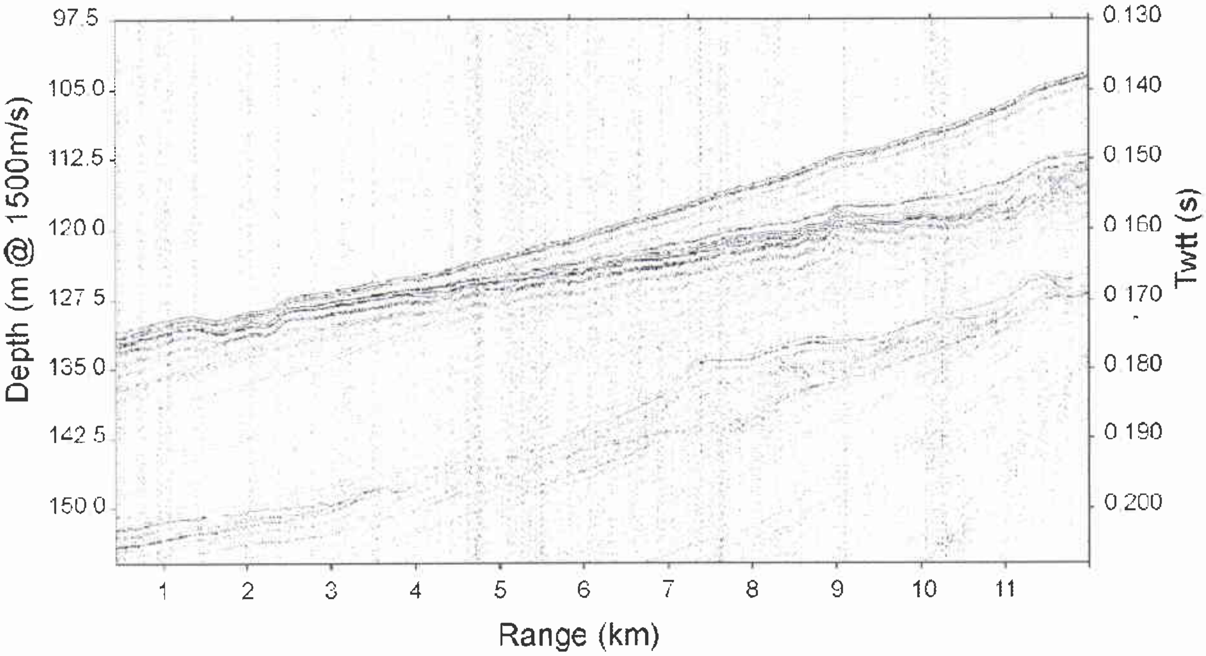

Figure 2 High resolution seismic reflection profile from the MAPEX 2000 experimental site.

4

Synthetic Data Analysis

When testing a new concept or technique it is often a good practice to evaluate synthetically generated data first. In this study, a "*proof-of-concept*" was provided using synthetic data that were set up to closely simulate the acoustic propagation through the MAPEX 2000 experimental environment. The environmental model was built using the available ground truth data and information from the work in [3].

Fig. 3 shows a schematic diagram of the synthetic environment. The experimental track was assumed to be 11km long with a linearly sloping bathymetry from 99m to 140m. The seafloor consisted of a single sediment layer over a semi-infinite basement. The sediment layer had a sound speed gradient of $\Delta = 1.5s^{-1}$ and the basement layer was iso-speed. The density and attenuation were assumed to be constant with depth.

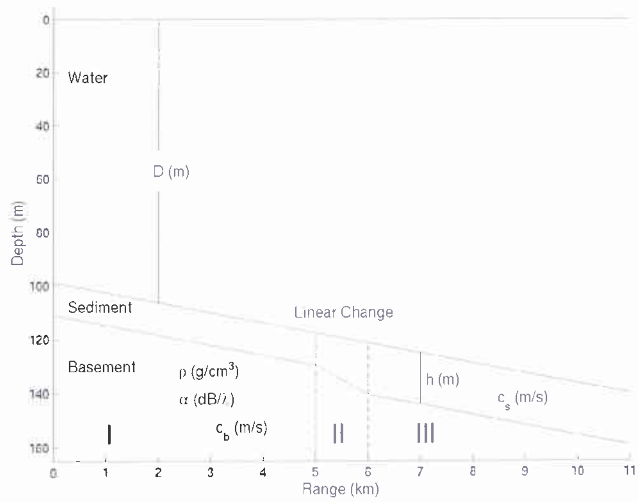

Figure 3 Diagram of the experimental set up for the synthetic test case.

The synthetic environment contained three different regions. Regions *I* and *III* had range-independent environmental properties (except water depth). The middle region contained environmental properties that varied linearly with range (Region

II). The properties in region *II* were constrained by the values in the two other regions. In Fig. 3 region *II* is the area from $5-6$km, delineated by the dashed lines. Table 1 shows the values of the environmental properties for regions *I* and *III*. The source depth was 60m, the receiver depth was 63.5m, the range, (R), between the source and the first receiver of the HA was 300m and the array length was 252m. The HA consisted of 64 sensors spaced 4m apart. The attenuation, (α), was constant over the entire seafloor at 0.1dB/λ.

Table 1 *Parameter values in regions I and III.*

Parameter	Region *I*	Region *III*
h (m)	9.7	18.9
c_s (m/s)	1480	1554
c_b (m/s)	1700	1664
ρ (g/cm^3)	1.2	1.8

Inversions were carried out at various points along the 11km track; over region *II* the inversions were done at more frequent intervals. Table 2 lists the reference points for the inversions. From this point onwards the inversions will be referenced by their position (i.e., the inversion with the source at 2500m will be called the 2500 inversion). The total propagation path was 552m and the parameter values that are obtained from the inversions are assumed to be estimates of the average parameter values over the path.

Table 2 *Reference points for the synthetic inversions. The numbers represent the source position in meters along the 11 km track.*

0	2500	4400	4600	5100
5200	5300	5400	5500	5600
5700	5800	5900	8500	10400

Finally, the synthetic acoustic data were generated using the parabolic equation model RAM [11]. RAM is a finite-element model that can provide very accurate estimates of acoustic propagation in both range-independent and range-dependent environments.

Fig. 4 shows the results of the inversions. Since the values obtained from the inversion are basically range-averages, they are plotted at the half-way point of the source-array configuration. Fig. 4(a) shows the water depth as a function of range. The results are excellent agreement with true parameter values. The only exception is the 4600 inversion which obtained a water depth that was approximately 6m shallower then the true value. The results for the sediment thickness are shown in Fig. 4(b). Again, the agreement is very good with the exception of the 4600 inversion; in this case the sediment thickness is about 6m deeper then the true value.

The fact that inversion 4600 appears to have erroneous values for the water depth and sediment thickness is not totally unexpected. Fallat et al. [12] found that when the sound speed in the sediment is lower than in the water column it can be difficult to accurately determine the water depth and the sediment thickness, but that the depth to the basement can be accurately determined. Fig. 5 shows the depth to the basement, it is clear that the inversion results are in excellent agreement with the true depth to the basement.

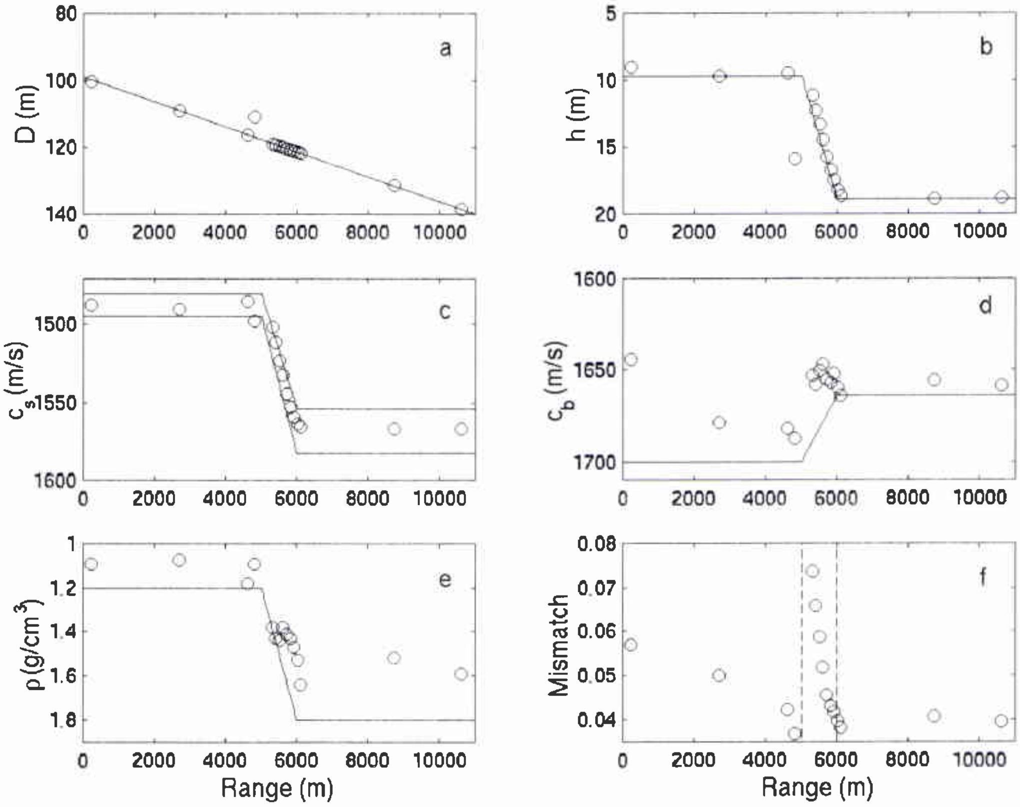

Figure 4 Inversion results for the synthetic data. The solid lines represent the true parameter values while the ∘ represent the parameter values obtained from the inversions. The dashed lines in (f) delineate region II where the properties changed linearly with range.

The synthetic environment consisted of a sediment layer that had a gradient but the model used during the inversions assumed an iso-speed sediment layer. Fig. 4(c) shows the results for the sediment sound speed, the top line represents the sound speed at the top of the sediment layer while the bottom line represents sound speed at the bottom of the layer. The inversion results are in good agreement with the

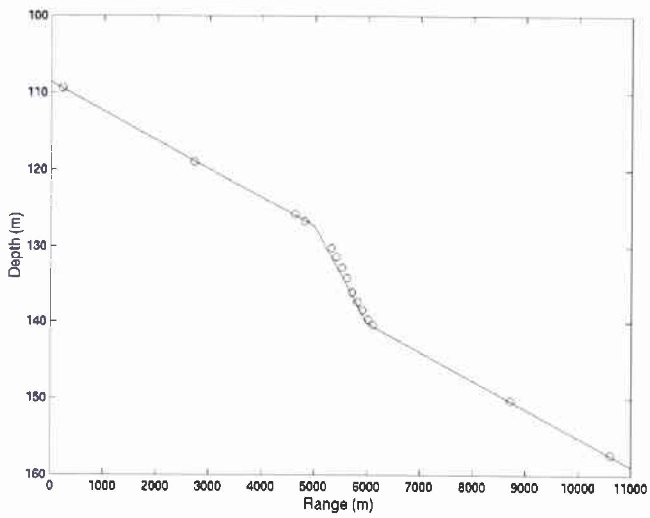

Figure 5 Inversion results for the basement depth.

true values, almost all points fall between the two lines.

Fig. 4(d) shows the results for the sound speed in the basement. These results appear to be poorly determined, but this can be explained as a systematic error due to the choice of parameterization. In all cases the basement speed found in the inversion was lower than the true speed and in regions I and III the difference between the inversion result and the true value was effectively constant. This is due to the fact that the sediment is modeled as an iso-speed layer. Modeling the sediment in this way means that at the sediment-basement interface the sediment speed will generally be lower then the true sediment speed. This introduces a systematic error that can be explained by considering the reflection coefficient given by [13]:

$$R = \frac{(\rho_b c_b / \sin\theta_b) - (\rho_t c_t / \sin\theta_t)}{(\rho_b c_b / \sin\theta_b) + (\rho_t c_t / \sin\theta_t)}. \tag{1}$$

In Eq. 1 the t denotes the properties of the top layer and b the properties of the bottom layer and θ represents a grazing angle. From this equation it is clear that if there is a lower value for the sediment speed at the sediment-basement interface then the sound speed in the basement must also be lower to match the reflection coefficient. In the inversions the data are only sensitive to the reflection coefficient at the sediment-basement interface and therefore the speed in the basement should be lower.

The results for the density are shown in Fig. 4(e). Again, this result appears to have a relatively constant offset (especially in regions I and III) which can be accounted for by a similar argument as the basement speed (see Eq. 1). Since the sediment and the basement have the same density the only boundary where density has an influence is at the water-sediment interface. In this case the sediment speed will generally be larger than the true value (because of the assumption of an iso-speed layer). The only way to compensate for the higher sound speed, and therefore match the reflection coefficient, is to have density that is lower.

Finally, Fig. 4(f) shows the final mismatches for the inversions. The measure of the mismatch was based on the Bartlett processor [14]:

$$E(\mathbf{m}) = 1 - \frac{1}{X}\sum_{j=1}^{X} \frac{|\mathbf{p}(x_j)\cdot\mathbf{p}^*(\mathbf{m},x_j)|^2}{|\mathbf{p}(x_j)|^2|\mathbf{p}(\mathbf{m},x_j)|^2}. \tag{2}$$

In this case the pressures were summed coherently in range and incoherently in frequency, therefore in Eq. 2 $X \geq 1$ is the number of frequencies, $\mathbf{p}(x_j)$ is a vector of acoustic pressures measured at the array, and $\mathbf{p}(\mathbf{m}, x_j)$ is the modeled acoustic pressures for a given model $\mathbf{m}$. In this form the mismatch can have values of $E \in [0, 1]$, with zero indicating a perfect match between the measured and modeled data.

The mismatches from the inversions ranged between 0.039 and 0.074 with an average value of 0.048. Although a few of the points in the middle region have higher mismatches it is clear that the range-dependent parameters did not result the inversion becoming unstable.

As a final check, RAM was used to model acoustic propagation along the full 11km track. This was done for three different cases:

1) the true parameter values,
2) the inversion results, and
3) average parameter values.

Average parameters were used because they are supposed to simulate the results of a long range inversion using VA data. Fig. 6 shows the transmission loss (TL) for 250Hz modeled at a VA of equally spaced sensors 11km away from the source. Fig. 6 (a) shows that the TL resulting from propagating through an environment built from the inversion results is in very good agreement with the TL from the true environment. Fig. 6 (b) shows that there is poor agreement between the TL from an environment derived from average parameters and the TL from the true environment. Fig. 7 shows same comparison of TL for a frequency of 800Hz. Again, the TL from an environment derived from the inversion results is in better agreement with the TL from the true environment then the TL resulting from an environment derived from average parameters.

Figs. 8 and 9 show the TL as a function of range and depth for the entire 11km track. The two figures are for 250Hz and 800Hz, respectively. In each case the field produced from the environment derived from the inversion results is in better agreement with the field from the true environment then the field from the environment built from the average parameters.

In general, the results of the inversions were in good agreement with the true parameter values. The only exceptions were the basement speed and density which appeared to be the result of a systematic error in the inversion. The synthetic case shows that using a towed HA to carry out a series of range-independent inversions (i.e., "*snap-shots*") over a range-dependent environment can accurately characterize the environmental properties. The following section will apply this technique to experimental data recorded in the Mediterranean Sea.

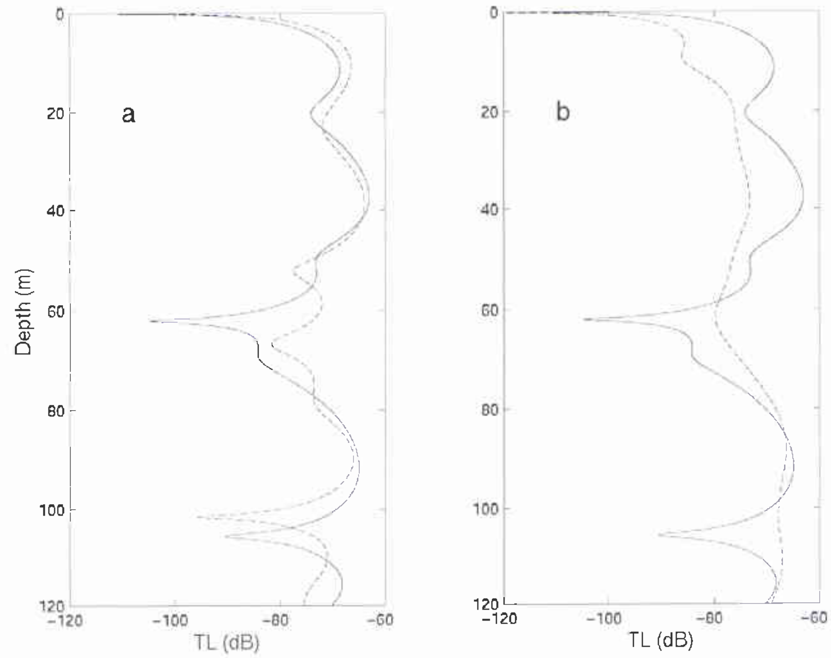

Figure 6 Transmission loss for 250Hz modeled at a vertical array after propagating the entire 11km track. In both cases the solid line represents the TL resulting from acoustic propagation through the environment with the true parameters. In (a) the dashed line is the TL when the environment is derived from the inversion results and in (b) the dashed line is the TL when the environment is derived from average seafloor properties.

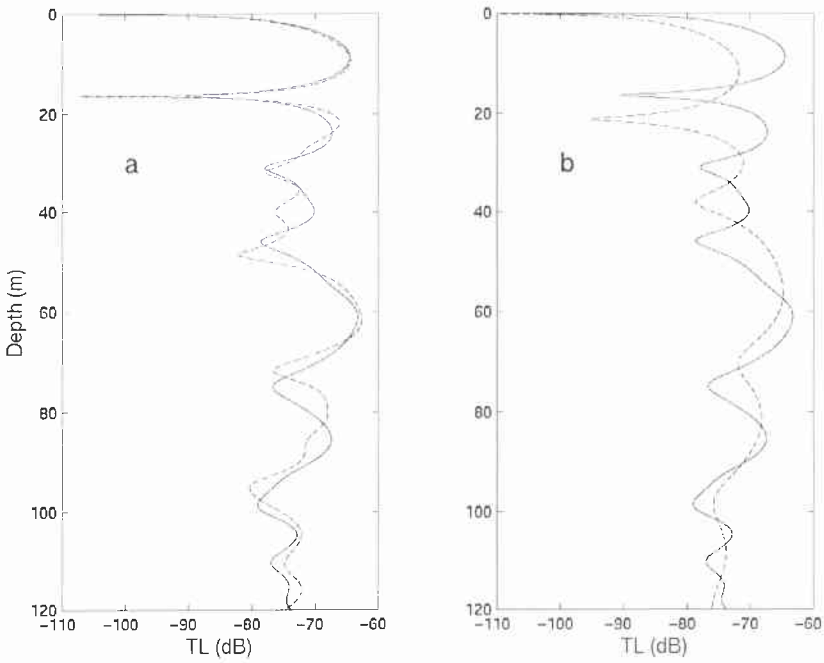

Figure 7 Transmission loss for 800Hz modeled at a vertical array after propagating the entire 11km track. In both cases the solid line represents the TL resulting from acoustic propagation through the environment with the true parameters. In (a) the dashed line is the TL when the environment is derived from the inversion results and in (b) the dashed line is the TL when the environment is derived from average seafloor properties.

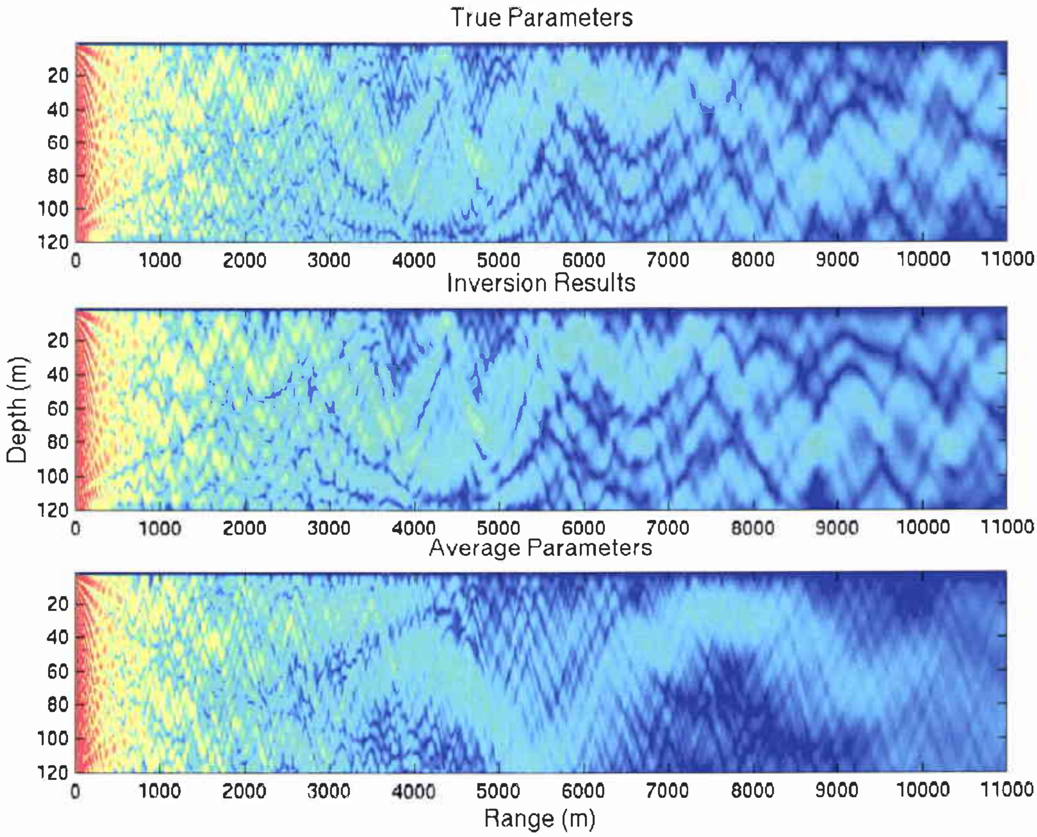

Figure 8 TL at 250Hz as a function of range and depth for the entire 11km track for the three cases.

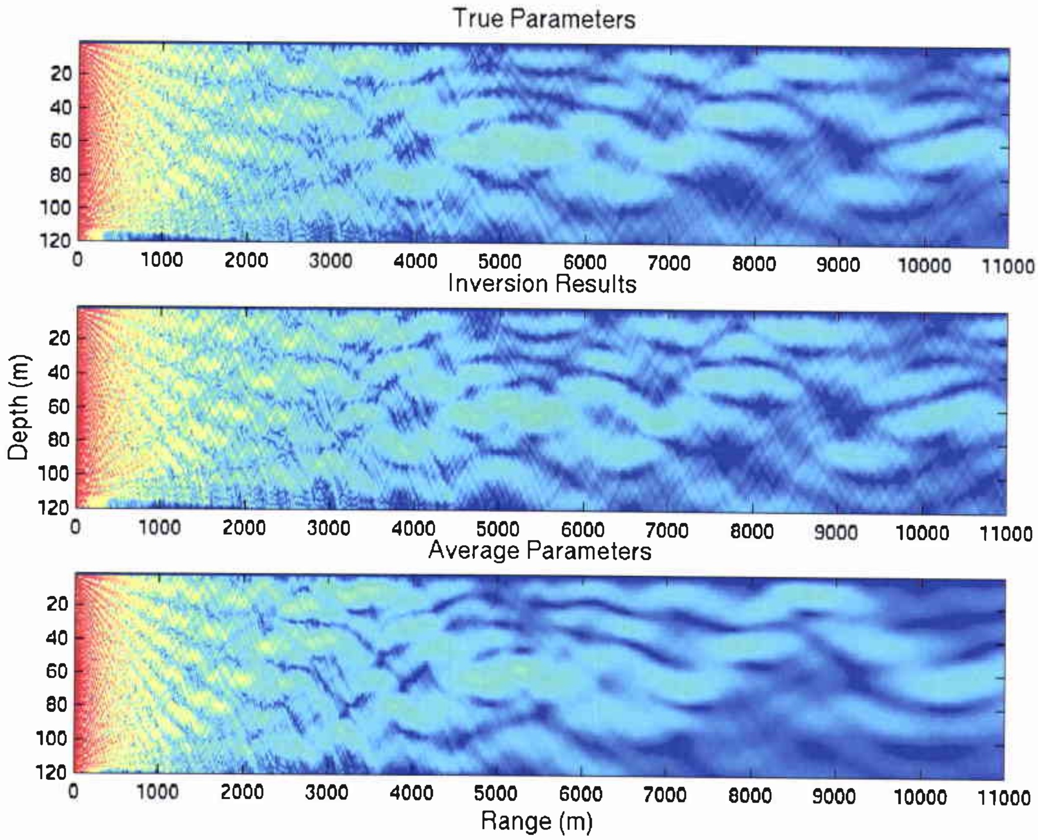

Figure 9 TL at 800Hz as a function of range and depth for the entire 11km track for the three cases.

5
Analysis of Experimental Data

5.1 Discussion of the Inversion Results

This section describes the results of the inversions of the MAPEX 2000 data. Fig. 10 shows the ship track with the corresponding points where data were analyzed and inversions were carried out. It should be noted that the ship was forced to make two course alterations during the run, and in these areas fewer data sets were analyzed because of the resulting deformation of the HA. For each set of recorded data several inversions were carried out and the results discussed here represent the inversion which produced the lowest mismatch.

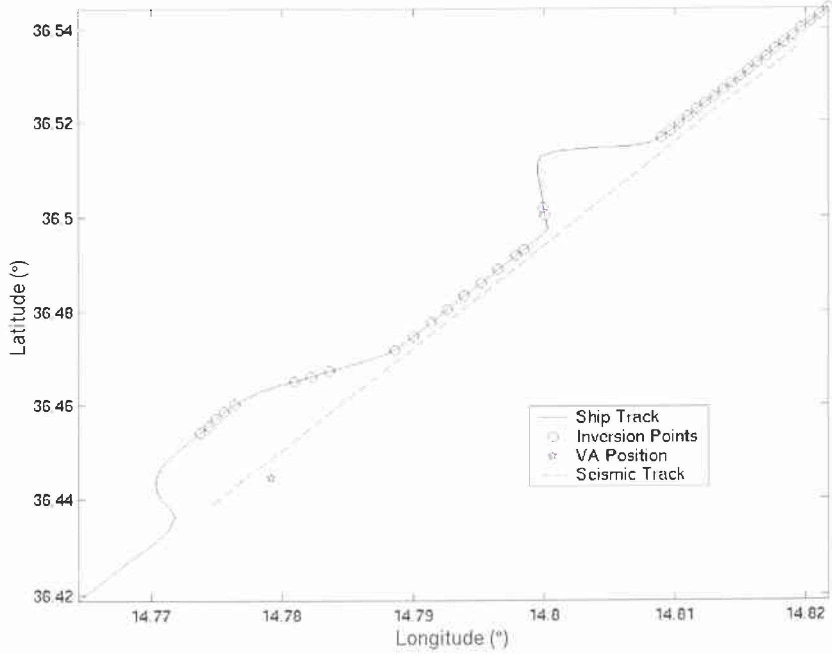

Figure 10 Diagram of the ship track including the points where inversions were done. Also included are the VA position and the high resolution seismic track.

Even though measurements were provided for the water depth, source depth and array depth, these parameters were included in the inversion because of the inherent errors associated with the measurement system and the modeling for the inversions. These measurements provided a useful guideline for setting up the search intervals. Table 3 shows the different parameters included in the inversion and their corresponding search intervals.

A simple two-layer model with the same set-up as the synthetic data inversions was employed for the real data inversions. A more complicated multiple layer model was evaluated but was found to produce poor results. The acoustic data was not able to resolve more layering structure therefore a more simplified model was warranted.

Table 3 *Parameter search intervals used for the inversion of MAPEX 2000 data. For D, the starting point for the water depth was changed as the measured depth increased but the search interval was always 15m.*

Parameter	Search Interval		Parameter	Search Interval
D	$0-15$ (m)		α	$0-0.5$ (dB/λ)
h	$0-25$ (m)		R (range)	$290-310$ (m)
c_s	$1450-1650$ (m/s)		z_{src}	$50-70$ (m)
c_b	$1600-1800$ (m/s)		z_{rec}	$50-70$ (m)
ρ	$1-2.5$ (g/cm^3)			

Fig. 11 shows the environmental parameter estimates determined during the inversion. Fig. 11 (a) shows the results for the water depth, D. The solid line is the water depth that was measured during the experiment. The first set of results, from 14.81° to 14.82° Longitude, have a good deal of variation around the measured water depth but the general trend of the sloping bottom is matched well. The remainder of the results match the measured water depth very well. The average difference between the measured and inversion result is 3m. Also, there is good agreement between the results using ORCA and the results using GAMARAY. This is an important result because to date very few people have used GAMARAY for geoacoustic inversion, especially at frequencies as low as 250Hz. This shows that GAMARAY is an effective propagation model for geoacoustic inversion.

The sediment thickness, h, is shown in Fig. 11 (b). Again, this parameter shows a lot of variability for the first set of results but this is not totally unexpected. This portion of the environment is characterized by a sediment layer that has a lower sound speed then the water column [3, 15]. The analysis of synthetic data in Sec. 4 and Fallat et al. [12] showed that for this type of environment the water depth and sediment thickness can be difficult to accurately determine. This is because the sediment layer appears acoustically similar to the water column. Even though these parameters are poorly constrained, their sum, that is the depth to the basement layer, is very well determined. Fig. 12 shows the estimated depth to the basement.

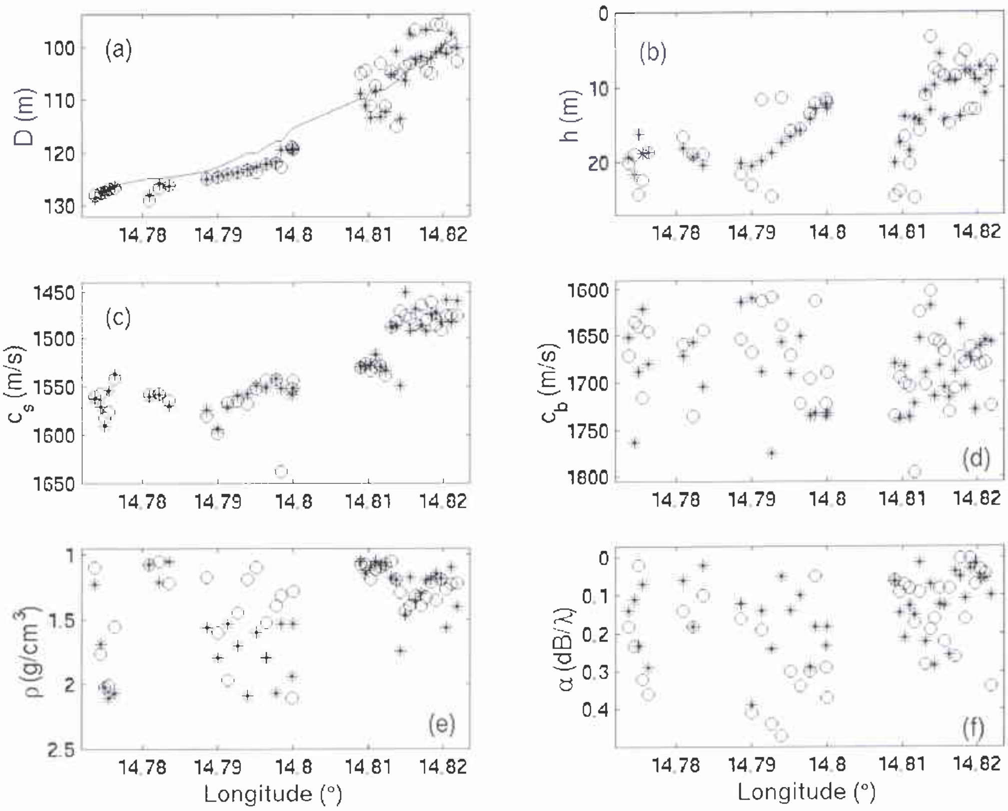

Figure 11 Inversion results for the environmental parameters from the MAPEX 2000 data. The $\circ$ represent the results of the inversions using ORCA and the $*$ are using GAMARAY, the solid line in the top left panel is the measured water depth.

It is clearly seen that the depth to the basement is a much more stable result. One noticeable feature is around 14.81°, the basement depth makes a dramatic change; this feature will be discussed later in Sec. 5.3.

Figs. 11 (c) and (d) show the inversion results for the sediment and basement sound speeds. The sediment sound speed is quite stable with the only clear change around 14.81°. This coincides with the same change in the basement depth mention above. The basement sound speed shows a good deal of variability compared to the sediment sound speed. Even so, most of the results still fall within [1650, 1750]m/s which is a reasonable range for basement sound speeds.

There are several possible reasons for the variability seen in the basement speed. First is that at high frequencies the acoustic energy is not penetrating deep enough

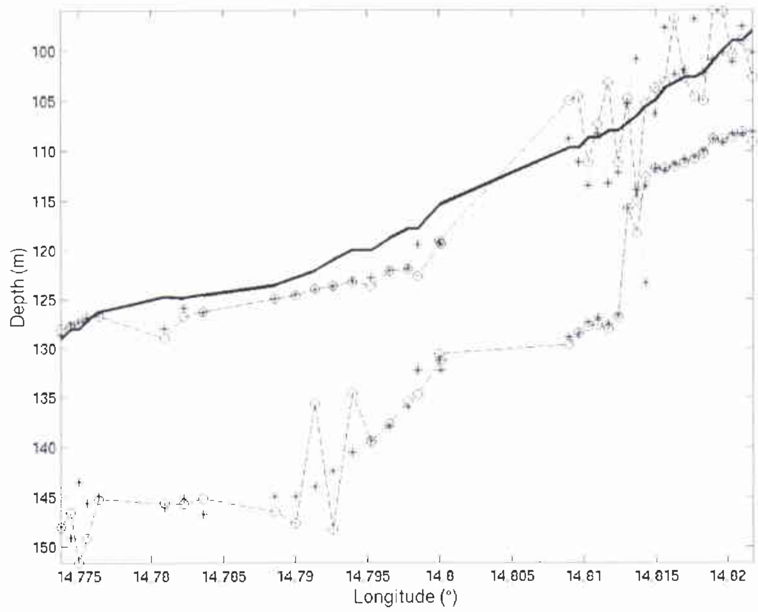

Figure 12 Inversion results for the effective depth to the basement. The solid line is the measured water depth, the top dashed and dotted lines are the water depths obtained form the inversions and the bottom dashed and dotted lines are the effective depth to the basement (i.e., $D_b = D + h$). The $\circ$ represent the results using ORCA and the $*$ are the results using GAMARAY.

into the seafloor, or not enough of the energy is returning to the array to accurately determine the basement sound speed. Another possibility is that the environment actually contains more than one sediment layer and that the basement speed is being averaged over several layers. A final possibility is that the experimental set up may not allow for a wide enough range of angles to properly sample the reflection coefficient.

The inversion results for the density are shown in Fig. 11 (e). There is some stability for the first set of results but the results become unstable around 14.81°. Finally, Fig. 11 (f) shows the attenuation, the results are very unstable which is expected since the attenuation will have little influence on the acoustic field over such a short propagation distance ($\sim$ 550m).

Fig. 13 shows the final mismatches between the measured and modeled acoustic fields. The measure of mismatch was again based on the Bartlett processor. In this case though, the pressures were summed coherently in frequency and incoherently in range, thus in Eq. 2 the X is the number of hydrophones, $\mathbf{p}(x_j)$ is a vector of acoustic pressures measured at the array, and $\mathbf{p}(\mathbf{m}, x_j)$ is the modeled acoustic pressures for a given model $\mathbf{m}$. The previous work in [3] had shown that using an objective function that was summed coherently in frequency and incoherently in range produced the best results for the MAPEX 2000 data. The reason for this was that the relative position of the hydrophones was not known well enough. The mismatches ranged from 0.17 – 0.48 and had an average value of 0.27. These values are well within expected mismatches for MFP inversion of real, noisy data [3, 12, 16, 17].

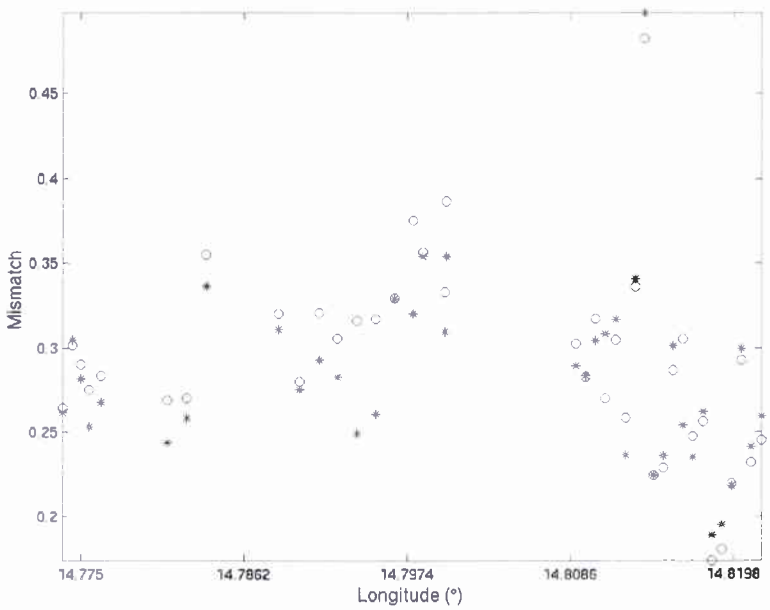

Figure 13 Mismatch from the inversions of the MAPEX 2000 data. The ○ represent the results using ORCA and the $*$ are the results using GAMARAY.

In each of the previously discussed figures the agreement between the inversion results from the two different models was very good. In cases were there was stability in the determined parameter (i.e., the parameter value did not vary a lot over the search space) both models produced very similar results. In cases were the parameters were not stable both models produced results that varied over roughly the same size of interval.

5.2 Comparison to Previous MAPEX 2000 Study

Siderius et al. [3] conducted a preliminary analysis of some of the MAPEX 2000 HA data. They looked at both HA and VA data from the MAPEX 2000 experiment, as well as synthetic data simulating the MAPEX 2000 experimental setups. In particular they concentrated on two different pings. The pings will be referenced by their time stamp and are pings 08 : 05 and 09 : 07.

The environmental model used in this study is very similar to the one employed by Siderius et al. [3] which means it is very straightforward to compare the environmental properties. Table 4 shows the results from the two different analyses for sound speeds in the sediment and basement, c_s and c_b, sediment thickness, h, and the density and attenuation in the half-space, ρ and α. The agreement between the two results are quite good except for the attenuation for ping 09 : 07.

Table 4 *A comparison of the results from Siderius et al. [3] and the present study.*

	Ping 08:05				**Ping 09:07**	
Parameter	Siderius et al.	Fallat 2002		Parameter	Siderius et al.	Fallat 2002
c_s (m/s)	1479.5	1475.8		c_s (m/s)	1552.4	1541.2
h (m)	9.7	9.2		h (m)	18.4	18.6
c_b (m/s)	1700.0	1678.3		c_b (m/s)	1666.5	1646.0
ρ (g/cm^3)	1.2	1.2		ρ (g/cm^3)	1.5	1.6
α (dB/λ)	0.1	0.1		α (dB/λ)	0.1	0.4

5.3 Discussion of the Basement Depth

In the discussion of the inversion results it was clear that some type of anomaly occurred around 14.81°. Not only did the basement depth dramatically change but changes were also seen in sediment sound speed and the density. It is thought that these changes are due to the fact that there were more layers that were not included in the inversion model.

Fig. 2 shows a high resolution seismic profile from the MAPEX 2000 experimental site (Fig. 10 shows the track for the seismic profile with respect to the ship track). At the beginning of the seismic profile two different reflectors can clearly be seen. The second, deeper reflector appears to have a constant separation of about $20m$ with the water-sediment interface. While the first reflector is an inclusion that gets larger with range.

Fig. 12 shows the inversion results for the depth of the basement D_b. If Figs. 12 and 2 are compared an interesting feature is observed. In the region before 14.81° the inversions produced results for the sediment thickness (h) that closely approximate the depth to the first reflector. After 14.81° the results obtained for h closely follow the second reflector. This is more evident in Fig 14. In this figure the results for the water depth and the depth to the basement layer have been overlaid on the seismic profile. After 14.81°, which is the area right of the 8km range marking, it is clear that the sediment depth closely approximates the depth of the first reflector and before 14.81°, the area to the left of the 8km range marking, there is a clear change in the sediment depth which then follows the depth of the second reflector. The inversion results have been slightly offset to provide a better comparison, this is an acceptable practice because the different analysis's will introduce slight errors. Another interesting feature is that before 14.81° the estimate of the water depth seems to follow the actual depth of the sediment layer, which is not entirely unexpected because the sediment is a slow speed layer which appears acoustically similar to the water column.

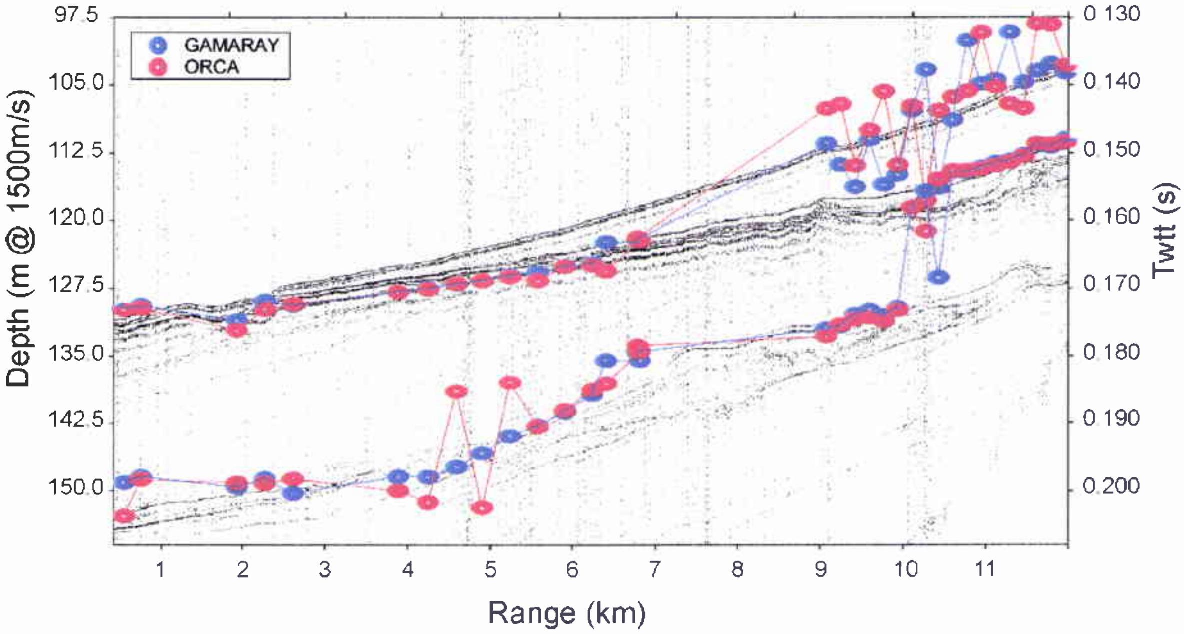

Figure 14 Inversion results of the water depth and the depth to the basement layer super-imposed on the seismic profile.

6

Evaluation of the Inversion Results

One of the goals of this analysis was to build a model of the environmental properties for a "real-world" situation. The previous sections have detailed how that was done and the actual results of the analysis. This section will show how the modeled data, created using the environment derived from the inversion results, compares to a different set of recorded acoustic data.

The data used in this section is VA data recorded at the same time as the HA data during the MAPEX 2000 experiment. Fig. 10 shows the ship track and includes the position of the VA. The same frequency range used for the inversion was utilized for these comparisons. For the comparison VA transmission loss (TL) data is compared to modeled TL data. The measured data was calibrated using a recorded source spectrum in the same way as the data in Sec. 5.

Fig. 15 shows the TL recorded during the experiment and modeled using the inversion results. In this case the source was $\approx$ 1.8 km from the array. A 10Hz frequency averaging was applied to obtain the TL (i.e., for 250Hz data from 245Hz - 255Hz was averaged). For almost all of the frequencies (the exception being the 250Hz data) the match is very good. It should be noted that the mean level has not been altered in any way, that is, no offset has been introduced to either TL measurement. This means that in general the data has been calibrated properly and that the attenuation is being modeled correctly.

Fig. 16 shows the comparison of the TL for a source-receiver range of $\approx$ 2.4km. The match is reasonably good but there is some degradation compared to that in Fig. 15. Finally, Fig. 17 shows the TL for a source-receiver range of $\approx$ 3.2km. The match is quite poor. There are a few features that are correlated but in general there is no agreement between the two TL's.

The results of this analysis can be used to determine an effective range where the inverted environmental properties would allow accurate modeling of the propagation in the true environment. It would appear that the modeling starts to break down somewhere between 2.4km and 3.2km away from the array. Therefore, it would not be appropriate to use this particular model for this experimental setup out to ranges greater then 2.5km.

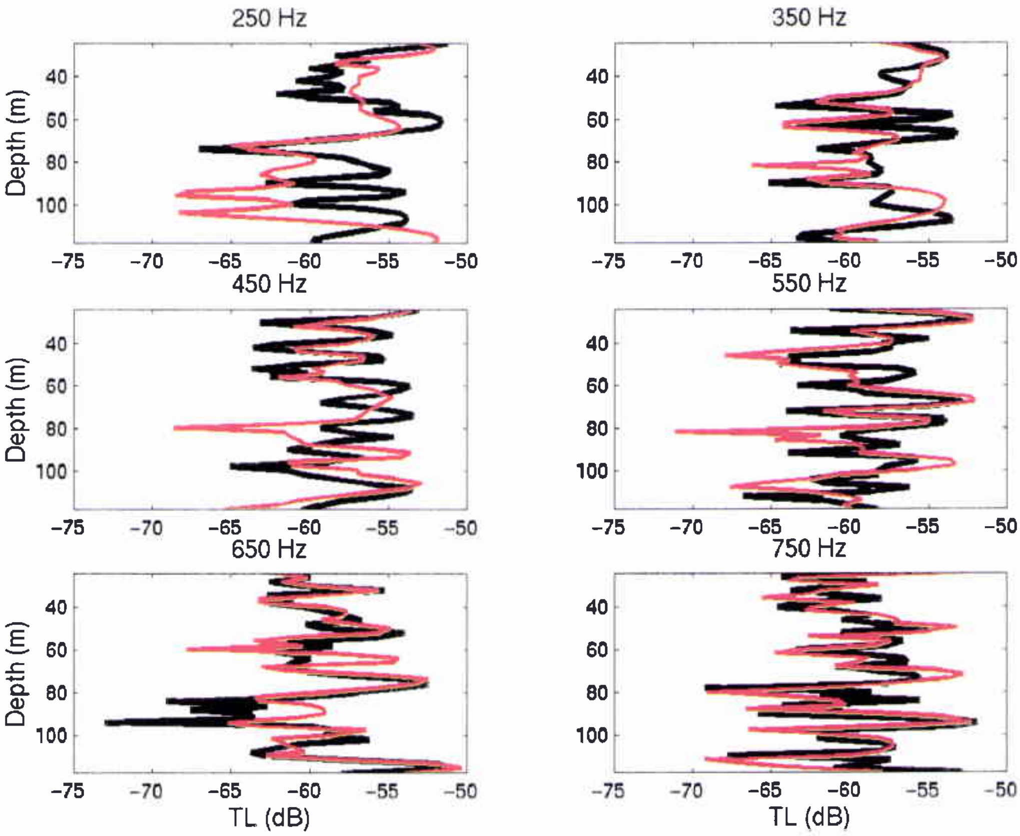

Figure 15 The measured and modeled TL for ping 09:07:00. The black line is the measured TL and the red line is the modeled TL. The source receiver range is ≈ 1.8 km.

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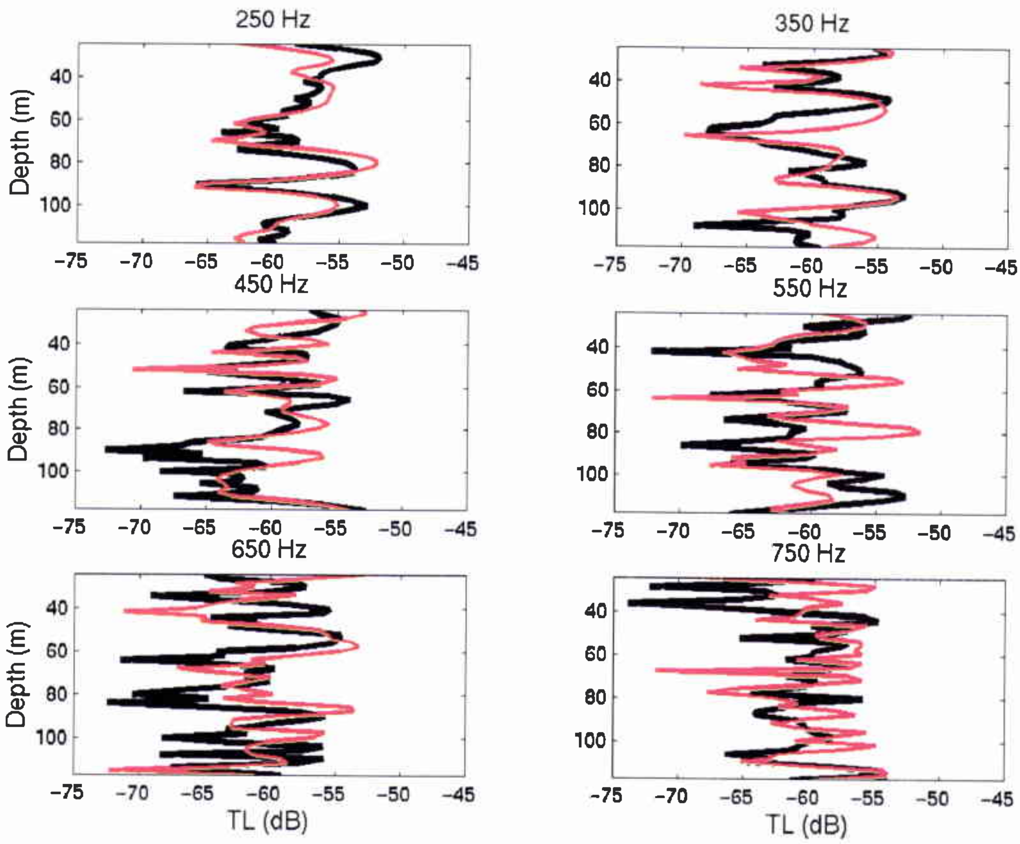

Figure 16 The measured and modeled TL for ping 09:03:00. The black line is the measured TL and the red line is the modeled TL. The source receiver range is ≈ 2.4 km.

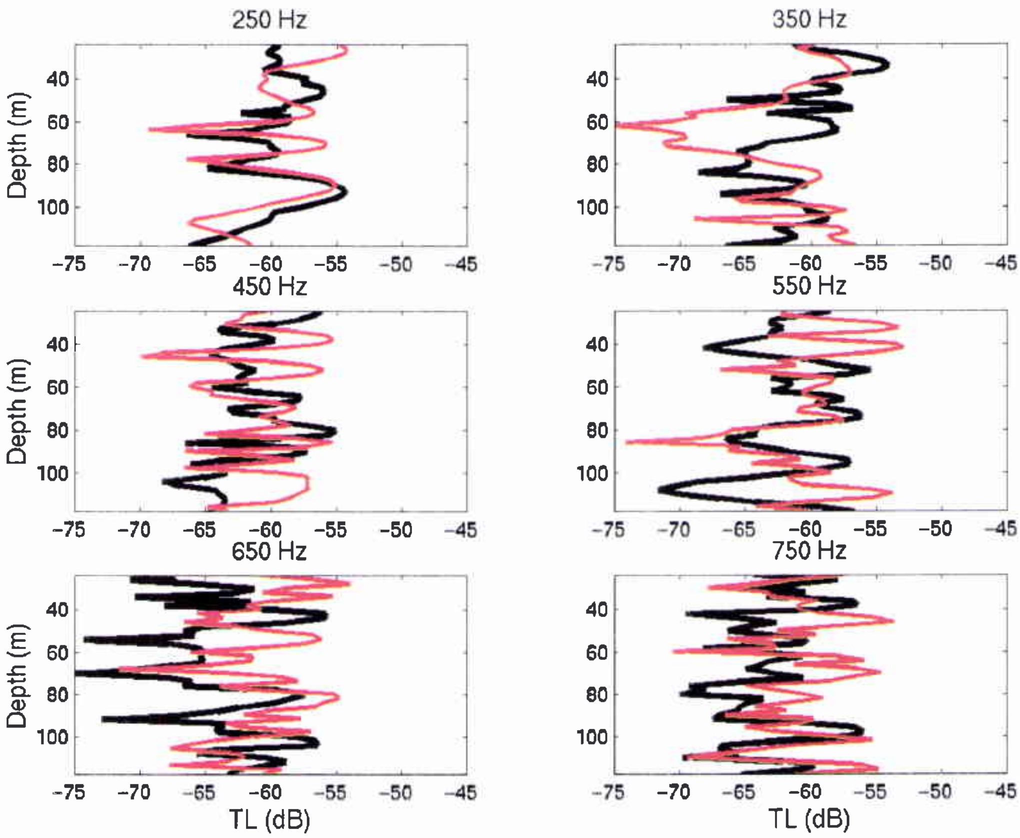

Figure 17 The measured and modeled TL for ping 08:57:00. The black line is the measured TL and the red line is the modeled TL. The source receiver range is ≈ 3.2 km.

7

Conclusions

It is a well known fact that in the littoral environment bottom properties have a significant influence on acoustic propagation. Therefore, it is a necessity to have a knowledge of these properties to accurately predict acoustic propagation in the littoral environment. Geoacoustic inversion techniques have provided a practical solution for estimating bottom properties *in situ* from recorded acoustic data. This paper outlined a new approach to the geoacoustic inversion problem. Generally geoacoustic inversion experiments use data recorded on a vertical array of sensors (VA); however, the work discussed here concentrated on the inversion of data recorded on a towed horizontal array of sensors (HA). The ultimate goal of the work was to characterize a range-dependent environment using data from a towed HA.

A synthetic study was carried out to validate the procedure and to pin-point potential problems with the technique. The synthetic data were designed to closely simulate the acoustic propagation through the experimental environment. The synthetic study showed that when the sediment sound speed was less then that of the water column, the inversion had the potential to produce erroneous estimates for the water depth and sediment thickness. This was not totally unexpected since other studies have shown similar results for that type of environment. The other feature that the synthetic study showed was that if an improper model is used, systematic errors can be introduced into the results. Ultimately, the analysis of synthetic data showed that the technique worked well. The estimates of the properties were in good agreement with the true values and that long range propagation to a VA could be well matched using the environment determined from the inversion.

The second phase of this work was to apply the technique to experimental data, in this case data from the MAPEX 2000 experiment was analyzed. The data consisted of LFM sweeps recorded on a towed HA. The experiment was conducted in the Mediterranean Sea off the south coast of Sicily in March of 2000. Inversions were carried out at numerous points along the ship track and these inversions were used to build up a description of the range-dependent environment. The results of the inversions showed that the technique was able to determine range-dependence for certain parameters, such as water depth, sediment thickness, sediment sound speed and the density. It also showed that for certain parameters, basement sound speed and the attenuation, there was very little chance of determining range-dependence or even stability in the results. When the results were compared with the available ground truth they were found to agree quite well. In particular, the results were in good agreement with a high-resolution seismic profile from the area. The estimated depth to the layers was approximated very well, especially considering that a simple one layer model was used. The results were also in good agreement with the previous study done on the MAPEX 2000 data [3].

As an additional analysis of the results, modeled TL was compared to measured TL from a VA. The VA was deployed at the same time as the HA and therefore provided another way to verify the results of the inversions. The inverted environment was capable of matching the measured TL up a distance of $\approx$ 2.5km. This is a significant result. It shows that even though the HA inversion produces results that agreed well with the available ground truth these results do not necessarily translate to propagation to a VA. This is also not completely surprising because the HA will have sensitivities to different bottom parameters then the VA.

This study has shown that it is possible to build a range-dependent model of an environment from a series of range-independent inversions of towed HA data. It is a future goal to apply this *"snap-shot"* approach to different and more complicated data, including greater range dependence and higher frequencies.

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Title

The characterization of a range-dependent environment using towed horizontal array data from the MAPEX 2000 experiment.

Abstract

The characterization of ocean environments using geoacoustic inversion techniques has received a lot of attention in recent years. Generally, the inversions are carried out on data recorded at a vertical array of sensors, which often produces good results but, from an operational stand point, can be difficult to accommodate. This paper describes the characterization of an ocean environment using data recorded on a horizontal array of sensors. Data from the MAPEX 200 experiment, conducted in the Mediterranean Sea in 2000, are used to determine seabed parameters for a range-dependent environment. A "*proof-of-concept*" is provided using synthetic data.

Keywords

Geoacoustic inversion – horizontal towed array – Strait of Sicily – Malta Plateau – matched field processing – genetic algorithms

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