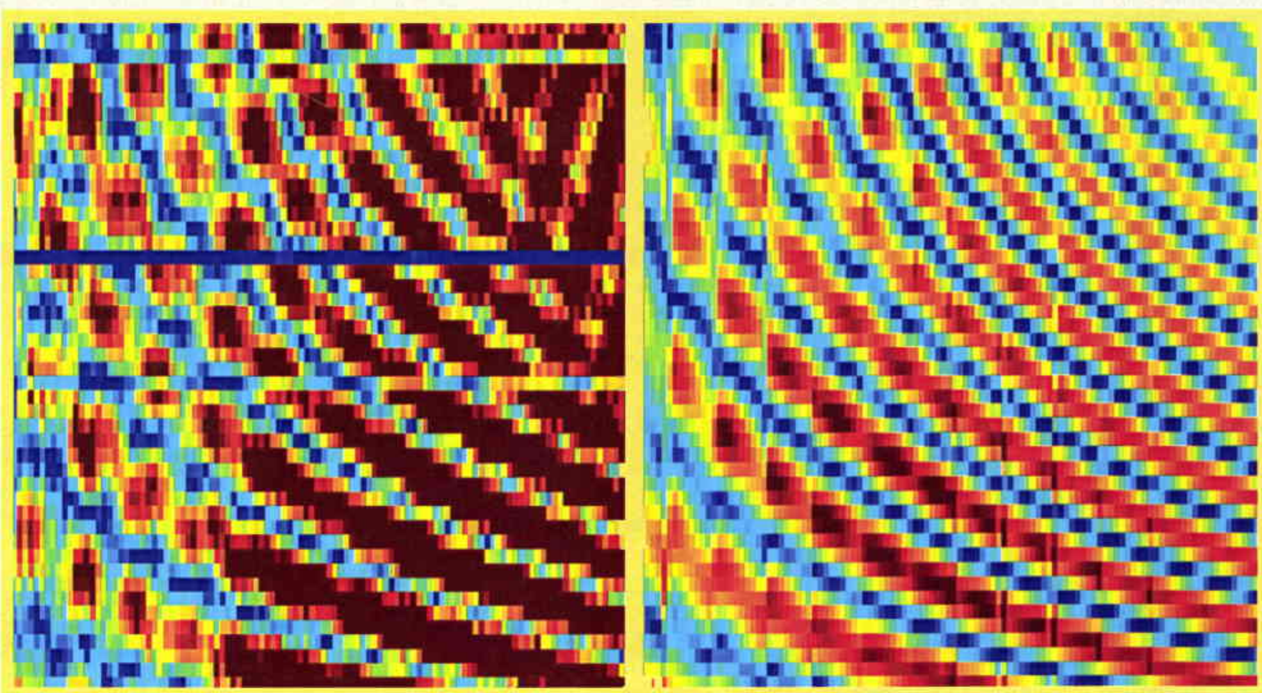
SACLANTCEN MEMORANDUM
serial no: SM- 332

Report no. changed (Mar 2006): SM-332-UU

SACLANT UNDERSEA RESEARCH CENTRE REPORT

Geo-acoustic inversion of the PROSIM '97 experimental data using simplex simulated annealing



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January 2000

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

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Jan L. Spoelstra
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Geo-acoustic inversion of the PROSIM'97 experimental data using simplex simulated annealing

M.R. Fallat, P.L. Nielsen and F.B. Jensen

Executive Summary:

The determination of sediment type is an important factor in the environmental assessment of shallow-water locations. For mine countermeasure operations, the sediment (seabed) can have a strong influence on the type and duration of the operation to be performed. For antisubmarine warfare operations, the sediment type influences the acoustic transmission loss and therefore the range of detection. The direct measurement of ocean bottom properties by core sampling, for example, is a difficult and time consuming process. The application of efficient inversion techniques on measured acoustic data makes it possible to extract average bottom properties in shallow-water regions by use of numerical simulations. A complete geo-acoustic inversion can be obtained within a few hours, which is an important factor in Rapid Environmental Assessment.

The inverted bottom properties for a specific location are often based on a single acoustic experiment. The question is whether results are reproducible when the season, experimental configuration and inversion technique are changed. In May 1997 SACLANTCEN performed a shallow-water experiment south of the island of Elba to address the issue of reproducibility of inverted bottom properties. A part of the experimental data was used in conjunction with a newly developed inversion algorithm for determining bottom parameters (e.g. sound speed and layering). The properties found are in good agreement with ground truth data, and previous geo-acoustic inversions for the same experimental area.

The geo-acoustic inversion results also demonstrate that it is possible to obtain repeatable values for the seabed parameters of this particular shallow-water area, irrespective of the environmental conditions and the numerical tools employed.

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Geo-acoustic inversion of the PROSIM'97 experimental data using simplex simulated annealing

M.R. Fallat, P.L. Nielsen and F.B. Jensen

Abstract: In the spring of 1997 SACLANTCEN performed an experiment near the Elba island in the Mediterranean Sea. The PROSIM'97 experiment was designed for the validation of a broadband acoustic propagation model. During the period of May 15-23 of 1997 both environmental data (i.e., sound-speed profiles, current measurements, temperature profiles, etc.) and acoustic data were collected. The data were collected from a well-known area where previous experiments have been performed. This report describes the geo-acoustic inversion applied to some of the acoustic data from this experiment. Estimates of the seafloor properties and the experimental geometry were determined from broadband acoustic pressure fields. The inversions were carried out using a new hybrid global optimization algorithm (simplex simulated annealing), and a new and fast acoustic propagation model PROSIM. A description of the inversion algorithm is given and the results of the inversions are presented and compared to past inversion results for this region.

Keywords: geo-acoustic inversion ∘ efficient broadband propagation model PROSIM ∘ hybrid inversion algorithm ∘ simplex simulated annealing

Contents

1
Introduction

In May 1997, SACLANTCEN performed an acoustic experiment near Elba in the Mediterranean Sea [1]. The aim of the experiment was to collect acoustic and environmental data in order to validate a broad-band acoustic propagation model (**PROSIM** [2]). The environmental data were measured at the same time as the acoustic data in an attempt to provide a useful comparison between modeled and experimental results. The experiment was carried out in a region of the Mediterranean Sea that is well known, with several previous experiments having been conducted there, see Refs. [3]-[7]. This region was chosen because of the pre-existing background data and to see if different experiments could produce similar results for a given area. This report describes the geo-acoustic inversion of a portion of the acoustic data collected during this experiment. The data were inverted using a new inversion algorithm based on simplex simulated annealing, and a new acoustic propagation model **PROSIM**.

The acoustic data used in this report were recorded on May 18 and consisted of two linear frequency modulated sweeps of 300–850 Hz and 850–1350 Hz. The source was towed at a depth of approximately 12 m along a 25-km track in about 130 m of water. This track included regions where the bathymetry was nearly range independent, and areas with strong range dependence. The data were recorded on a vertical line array (VLA) of 48 hydrophones which spanned a large portion of the water column (from 26–120 m with a 2 m spacing between each hydrophone).

The goal of the inversion was to obtain geo-acoustic and geometric parameters from the measured acoustic data. The following section provides a description of the inversion algorithm used. Sec. 3 contains a brief overview of the **PROSIM** acoustic propagation model and a description of the synthetic inversions carried out to determine the properties needed for the real data analysis. In Sec. 4, a description of the experiment is given, and the inversion results are summarized and compared to results from previous experiments in the region. Finally, the conclusions of this work are given in Sec. 5.

2

Inversion algorithm

The problem of determining geo-acoustic and geometric parameters from measurements of ocean acoustic fields has received considerable attention in recent years (e.g., Refs. [8]-[12]). The problem can be formulated by assuming a discrete model of unknown parameters $\mathbf{m} = \{m_i, i = 1, ..., M\}$ and by defining an objective function $E(\mathbf{m})$ which represents the mismatch between the measured and modeled acoustic fields. The aim of the inversion is to search a pre-defined parameter space for the model $\mathbf{m}$ which minimizes the mismatch E. This can be difficult because the parameter space can be very large, and can contain a large number of local minima. Therefore, global optimization techniques such as simulated annealing (SA) [8, 9] or genetic algorithms (GA) [10, 11] have typically been applied to this problem. Simplex simulated annealing (SSA) [12] is a hybrid global inversion algorithm which combines the downhill simplex method (DHS) [13] and SA in an attempt to produce a more efficient inversion algorithm. In this section brief descriptions of DHS, SA, and SSA are given. For a more detailed discussion of these algorithms see the literature cited above.

2.1 *The downhill simplex method*

The DHS method [13] is an intuitive geometric scheme for moving downhill in parameter space. The method is based only on function evaluations and does not require calculating derivatives or solving systems of equations. DHS operates on a simplex of $N + 1$ models in an N dimensional space [e.g., Fig. 1 (a), for $N = 3$]. The algorithm takes a series of steps in order to work its way downhill. Each model in the simplex is ranked according to its mismatch E. The method starts by trying to improve the model with the highest mismatch by reflecting it through the face of the simplex containing the lowest mismatch model [Fig. 1 (b)]. If this new model is now the lowest mismatch model, an extension in the same direction is attempted [Fig. 1 (c)]. If the reflected model is still the highest mismatch model, the reflection is rejected and a contraction is performed [Fig. 1 (d)]. If none of these steps lead to a decrease in the mismatch E, then a multiple contraction about the lowest mismatch model is carried out [Fig. 1 (e)]. This process is repeated until a user-specified criterion is met or a maximum number of steps have been performed.

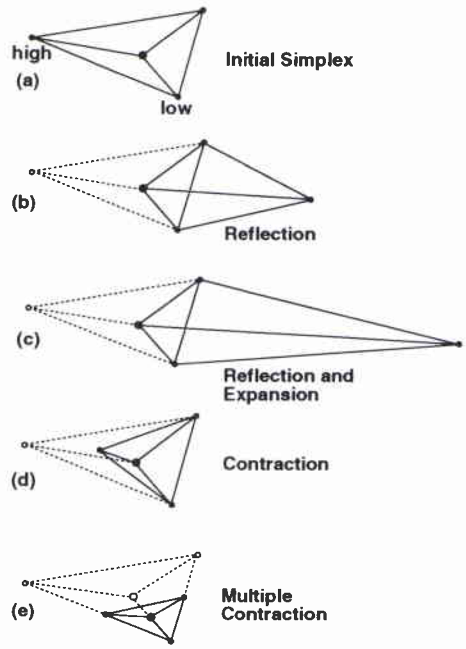

Figure 1 *Types of steps attempted by the DHS algorithm in three dimensions.*

2.2 Simulated annealing

Simulated annealing [8, 9] is based on an analogy to the thermodynamic process of annealing. The algorithm consists of a series of iterations involving random perturbations to a set of unknown model parameters. After each iteration, a control parameter, the temperature T, is reduced slightly. Perturbations which decrease the mismatch E are always accepted, while perturbations which lead to an increase in E are accepted with a probability given by

$$P(\Delta E) = \exp(-\Delta E/T). \tag{1}$$

Allowing the algorithm to accept increases in E gives it the ability to escape from local minima in search of a better solution. The annealing schedule, defined by the starting T, rate of reducing T, and the number and type of perturbations is an important component of the SA algorithm. Adopting an annealing schedule that is too fast can lead to sub-optimal solutions, while a schedule that is too slow can waste computation time. In order to determine an effective annealing schedule some experimentation is generally required.

2.3 Simplex simulated annealing

Simplex simulated annealing [12] is a hybrid technique combining the DHS method and a fast SA algorithm [14]. Unlike standard SA, the SSA operates on a simplex of models and not just a single model. Also, instead of purely random perturbations of the model parameters, DHS steps with an added random component applied. The procedure to introduce the random component into the DHS steps is subtle, but effective. The steps are not computed using the current simplex of models, but rather using a secondary simplex which is created by applying random perturbations to all the model parameters and mismatches of the current simplex. The perturbations to the model parameters are computed using a temperature-dependent Cauchy distribution [15] given by

$$m_i = m_i^{'} + \xi\Delta_i, \tag{2}$$

where $m_i^{'}$ is the value of the model parameter prior to the perturbation, Δ_i is a random variable uniformly distributed on the interval $[-\Delta m_i, \Delta m_i]$, where $\Delta m_i = m_i^+ - m_i^-$ (m_i^+, m_i^- are the upper and lower bounds of the search interval), and ξ is a Cauchy-distributed random variable computed as

$$\xi = [T_j/T_o]^{1/2}\tan[\pi(\eta - 1/2)]. \tag{3}$$

In Eq. 3, η is a uniform random variable on $[0, 1]$ and T_j is the temperature at the jth step. The perturbation to the mismatch is computed according to

$$E = E^{'} + \xi\bar{E}, \tag{4}$$

where ξ is given by Eq. 3, $E^{'}$ is the current mismatch, and $\bar{E}$ represents the average mismatch of the current simplex. This procedure leads to DHS steps that are not always downhill. Each proposed DHS step is evaluated for acceptance using the probabilistic criterion of SA (i.e., Eq. 1). This provides a mechanism for accepting uphill steps and escaping local minima. The accepted steps are used to update the current simplex. The secondary simplex is recomputed after each DHS step, whether this step is accepted or rejected. Once the SSA algorithm has completed the predetermined number of iterations, a quenching is carried out to make sure the bottom of the closest minimum has been reached. This is accomplished by setting the temperature to zero and employing the standard DHS method. A block diagram illustrating the basic SSA algorithm is given in Fig. 2.

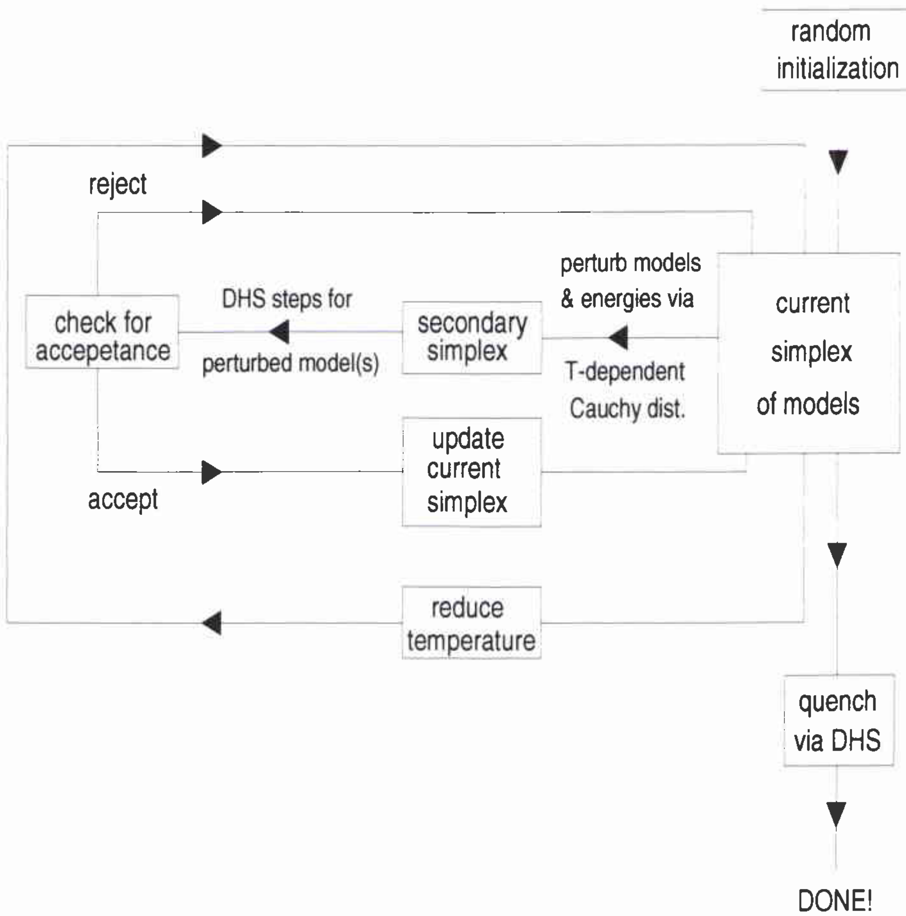

Figure 2 *Simplified block diagram illustrating the SSA algorithm.*

A final comment about the SSA algorithm has to deal with efficiency. During a multiple contraction, the mismatch of all but one of the models must be recalculated. In the early stages of the inversion the additional computational expense of performing multiple contractions is generally wasted. The SSA algorithm can be made more efficient by introducing a simple procedure which allows some fraction of the multiple contractions to be performed. This fraction can be small (or zero) in the early stages of the inversion, and can be increased to a final value of unity for the late stages.

3

Inversion of synthetic data

Synthetic test cases were run to determine the different parameter sensitivities and to discover an effective annealing schedule before the inversion was applied to the experimental data. The synthetic data were generated using PROSIM, which is a range-dependent version of the existing ORCA [16] normal-mode acoustic propagation model. The range dependence was built into the model using the adiabatic approximation [17]. Another feature of PROSIM is that it computes the acoustic field using only the real wavenumber axis (this is an option in ORCA). To simulate the experimental data the ocean environment was based on the inversion results from previous experiments conducted in the same region [6, 7]. Figure 3 is a simple schematic diagram of the ocean environment and gives the parameter values used. In an attempt to conserve time, the synthetic cases only made use of the 300–850 Hz band.

The objective function used for the inversions was the Bartlett or linear processor summed coherently in depth and incoherently in frequency:

$$E(\mathbf{m}) = 1 - \frac{1}{F}\sum_{i=1}^{F} \frac{|\mathbf{p}(f_i)\cdot\mathbf{p}^*(\mathbf{m},f_i)|^2}{|\mathbf{p}(f_i)|^2|\mathbf{p}(\mathbf{m},f_i)|^2}, \tag{5}$$

where F is the number of frequency components, $\mathbf{p}$ is the measured acoustic field, and $\mathbf{p}(\mathbf{m})$ is the modeled acoustic field for a particular model $\mathbf{m}$. The model was defined by the water depth D_1, sediment thickness h, sediment compressional speed c_s, basement compressional speed c_b, source range r and depth z, and the array tilt (measured as a horizontal displacement of the top hydrophone while holding the bottom hydrophone fixed).

Figure 4 shows the results of a synthetic inversion. Figure 4(a) is the mismatch of all models in the simplex while (b-h) shows the convergence of the model parameters with the dotted lines indicating the true parameter value. Parameters such as c_b, r, z, and the array tilt are quite sensitive and lock into the correct value early in the inversion. For the other parameters (D_1, h, c_s) it can be seen that even for a low mismatch of 10^{-3} (which occurs around temperature step 400–500) the true value is still not found. Therefore one can assume that D_1, h, c_s are less sensitive parameters because even for lower mismatches, the data can not resolve the true

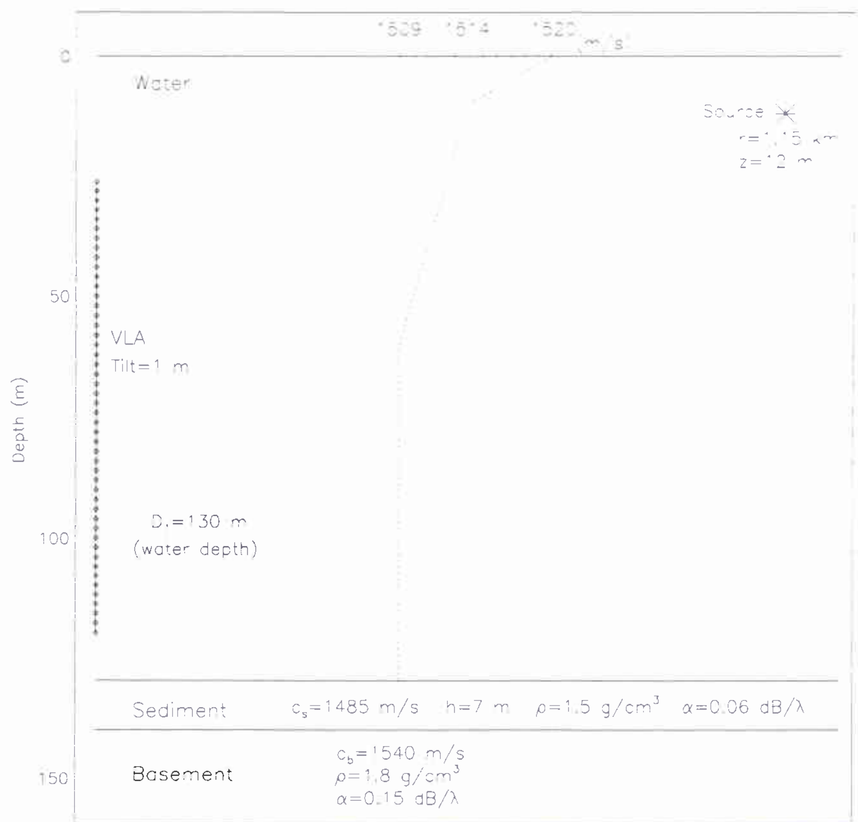

Figure 3 *Schematic diagram of the synthetic ocean environment used in the inversions.*

parameter values.

Correlation between parameters can make an inversion even more difficult to solve. In this example a direct correlation is known to exist between the sediment thickness and the sediment compressional speed. This correlation is suggested in Fig. 4 (c, d), where the thickness and sound speed appear to track each other throughout the inversion (i.e., when the thickness decreases so does the compressional speed). A correlation is also thought to exist between the sediment properties and the water depth. This correlation arises from the fact that the sediment has a very low compressional speed (i.e., lower than in the water column) and a small attenuation (although the attenuation is still much larger than in the water column). A trade-off between D_1, h, c_s is created because the sediment acoustically appears as part of the water column and therefore it is difficult to accurately determine these properties.

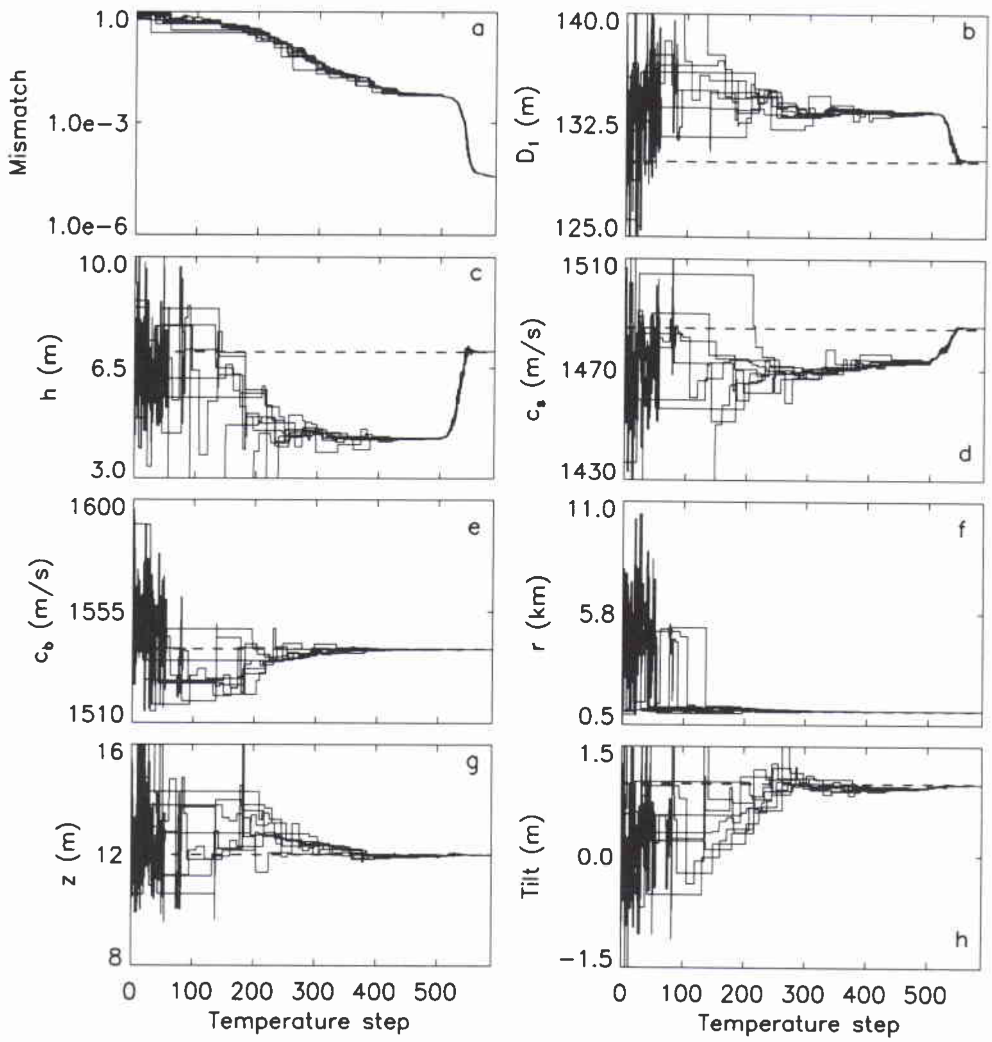

Figure 4 *The inversion results for a synthetic test case including the mismatch E and all model parameters. The dashed lines indicate the true parameter values, and the range of ordinate values indicate the search interval.*

4
Inversion of experimental data

The experimental site was south-east of the Elba island in the Mediterranean Sea, off the west coast of Italy (Fig. 5). The data used here were recorded along track A and consisted of two linear frequency sweeps of 300–850 Hz and 850–1350 Hz [1]. The data were recorded on a vertical array of 48 hydrophones (one hydrophone was omitted because the gain was too low). The source was towed at a nominal depth of 12 m for about 25 km, passing close (approximately 700 m) to the array. Figure 6 is a sample of one of the acoustic signals recorded at the closest point of approach on a mid-water column hydrophone. The first received pulse seen in Fig. 6 is a sweep of 300–850 Hz and the second pulse 850–1350 Hz separated by 2 s.

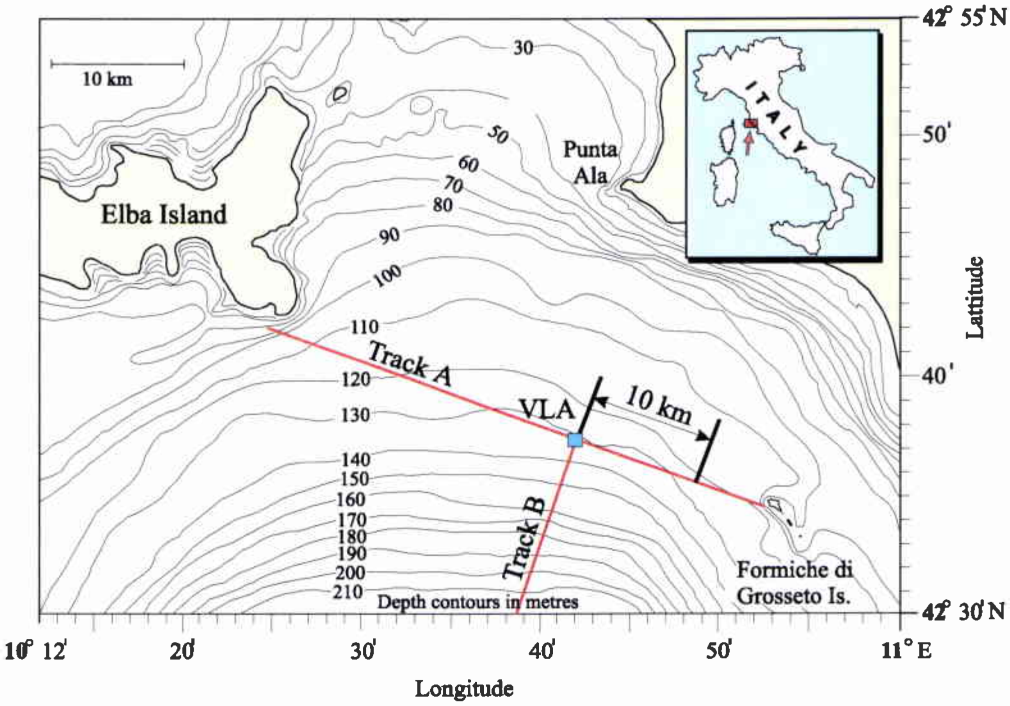

Figure 5 *South Elba experimental site. The inversions in this paper are from data taken along Track A.*

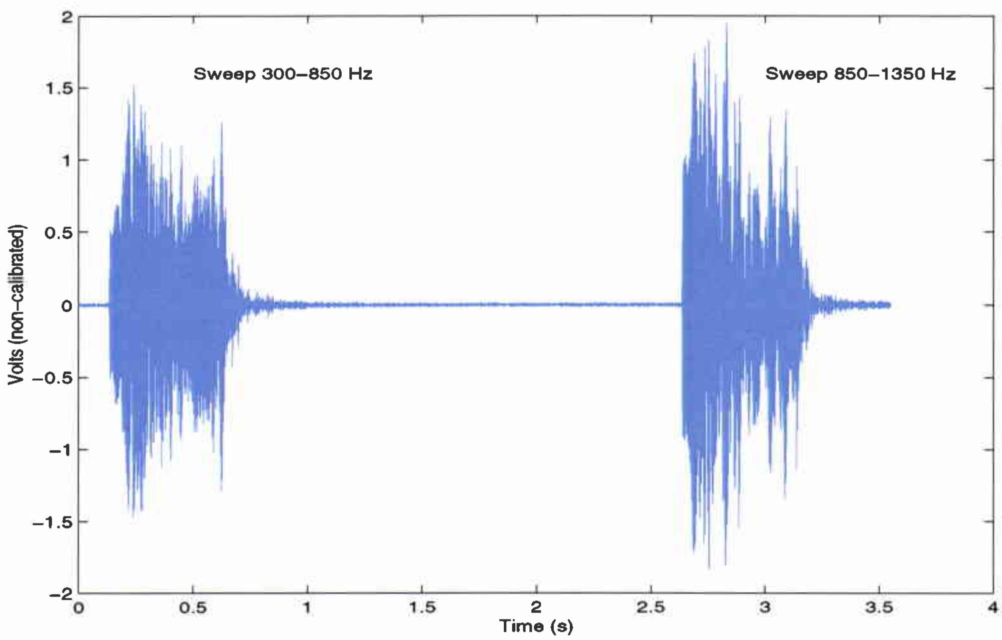

Figure 6 *Acoustic signal recorded on a mid-water hydrophone at the closest point of approach. The first received pulse is a linear frequency modulated sweep of 300–850 Hz and the second pulse 850–1350 Hz separated by 2 s.*

The source and a CTD-chain was towed simultaneously by *R/V Alliance* providing accurate sound-speed along the tracks as the acoustic signals were transmitted. Bathymetric data were provided by a swath multibeam echosounder. Generally swath data measurements are accurate to within approximately 0.5%. However, in this case the swath system was not properly calibrated and therefore the measurements are thought to have an error of approximately 10%. This uncertainty was accounted for by increasing the search bounds on the bathymetry. The range dependence proved to be more important than originally expected (even though the slope was no larger than 0.3°) because the change in bathymetry corresponded to about three wavelengths at the highest frequency. Therefore, the inversion was carried out using a range-dependent bathymetry.

PROSIM models a sloping (range-dependent) bathymetry using a number of discrete segments. Determining an appropriate number of segments to represent a particular slope is important because too few segments will not model the slope properly while too many will waste valuable computation time. To determine the right number of segments for a particular slope, a simple convergence test can be applied. The test was conducted on a 0.2° up–slope with a water depth of 130 m at a range of 0 km and 125 m depth at 1.5 km range. Ten segments were assumed to be the upper bound for an acceptable number of segments for modeling the slope (previous test were done comparing PROSIM to other propagation models and it was found that for this slope ten segments were adequate) . Therefore, the goal of the convergence test was to determine the minimum number of segments required to accurately model the ten segment case. Fig. 7 (a-c) shows examples of a 0.2° slope modeled with two, five, and ten segments. Fig. 7 (d) is a plot of the acoustic pressure on a mid-water hydrophone for all three cases. The two segment case (dotted) has a poor agreement with the ten segment case (solid), while the five segment case (dashed) agrees to an acceptable level of mismatch with the ten segment case. The acceptable level was taken to be a Bartlett mismatch of 10^{-3}, since the inversions of the real (noisy) data were not expected to achieve levels below this. Therefore, modeling this type of slope with five segments should be sufficient.

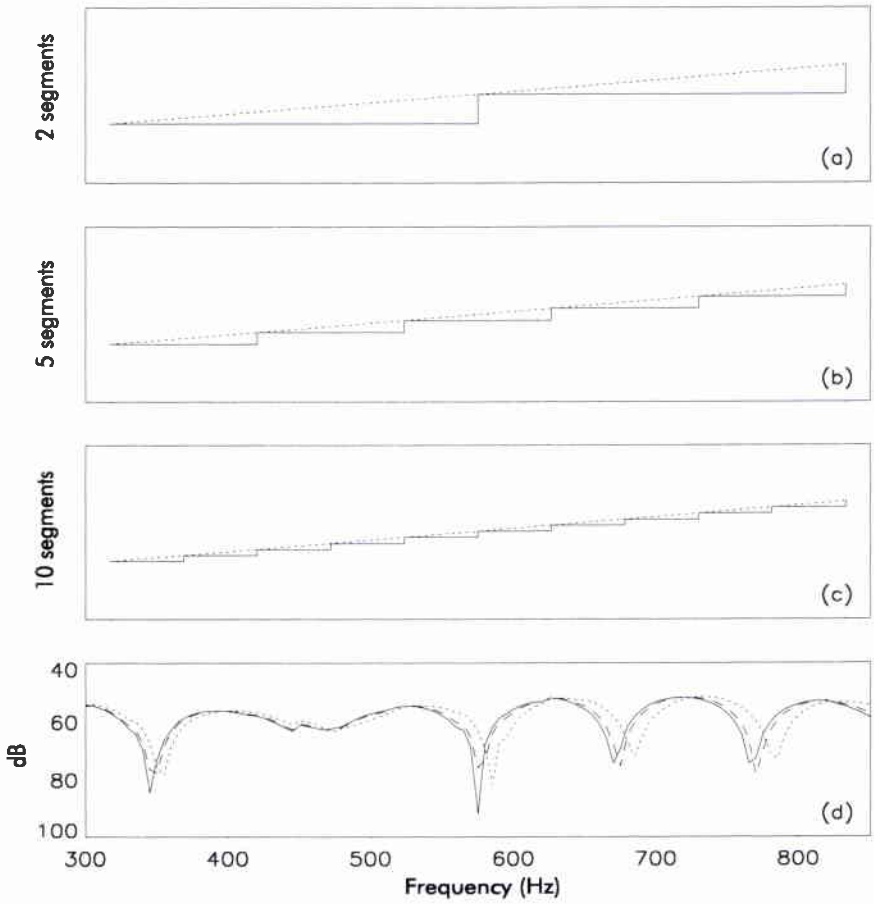

Figure 7 *Modeling a slope using different numbers of segments (a–c for two, five, and ten segments). The acoustic pressure (d) for a mid-water hydrophone for two (dotted), five (dashed), and ten (solid) segments.*

4.1 *Inversion results*

The environmental model used for the inversion of real data was similar to that used in the range-independent case except that a second water depth was added. The water depths now correspond to measurements at the VLA (D_2) and at the source (D_1). Only the bathymetry was varied with range, all other unknown parameters were assumed to remain constant. The depth and the range of the segments (used to describe the slope) were defined by D_1, D_2, and r using the following relationships:

$$d_i = D_1 - \Delta d \times i, \qquad \Delta d = \frac{D_1 - D_2}{5}, \qquad i = 0,..,5 \tag{6}$$

$$r_i = \Delta r_i \times i, \qquad \Delta r_i = \frac{r}{5}, \qquad i = 1,..,5, \tag{7}$$

where d_i and r_i represent the depth and range of the i^{th} segment.

The data consisted of recordings of acoustics signals transmitted every two minutes from a source being towed at approximately four knots (see Fig. 8 (a) which shows the ship track and the VLA position).

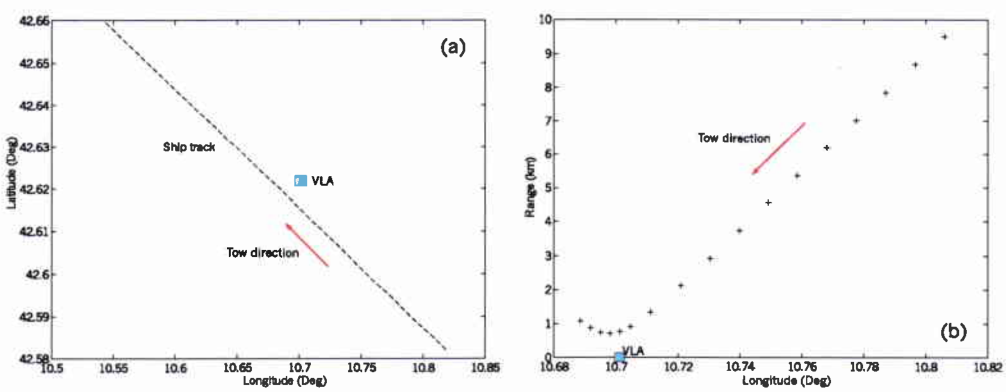

Figure 8 *Plot of the ship track and the VLA position is given in (a). In (b) the crosses correspond to the approximate position of the source for each pulse. This plot contains all pulses used in the inversions. The approximate range to the source from the VLA versus the longitude is also shown in (b).*

Only the first pulse (300–850 Hz, in 5 Hz bands) was used in the inversions. This pulse was used because it produced more consistent results than both pulses combined and required half as much computation time. Also, some concern has been expressed about the success of matched-field methods when higher frequencies (> 400 Hz) are used [18]. The problem with using higher frequencies is that environ-

Table 1 *Pulses used in the inversions (time in UTC) and the approximate ranges (km) from the source to the VLA.*

095003 / 9.50	102600 / 4.55	105557 / 0.76
095602 / 8.68	103159 / 3.74	105757 / 0.71
100202 / 7.85	103758 / 2.93	105957 / 0.74
100802 / 7.01	104358 / 2.12	110157 / 0.88
101400 / 6.19	104958 / 1.35	110357 / 1.08
102000 / 5.36	105357 / 0.91	—

mental and experimental errors such as array position, sound speeds, etc have more influence and therefore make the inversion more difficult.

In order to obtain a detailed description of the environment without inverting all the data, every third pulse was taken. The exception to this was close to the array where every pulse was analyzed. Table 1 lists the pulses used in the inversions and the approximate range from the source to the VLA. Fig. 8 (b) shows the approximate range to the source from the VLA as a function of longitude. The closest point of approach was approximately 700 m, which corresponds to the pulse recorded at 10:57:57 UTC on May 18. From this point on, all pulses are referred to by their time, e.g., the pulse that was recorded at 10:57:57 will be called pulse 105757. The tow started close to the Formiche islands passed by the VLA and then moved closer to Elba.

Multiple inversions were run for each pulse and the results (summarized in Fig. 9) represent the single inversion that produced the lowest mismatch. Figure 9 (a) shows the range from the VLA, plotted with the same orientation as Fig. 8 (b), but it is plotted as a function of inversion number rather than longitude. The dotted line represents the approximate range calculated using the ship track (DGPS) and the VLA position, the crosses (and solid line) indicate the inversion results. The maximum difference between the two range measurements was about 350 m, and the minimum was approximately 7 m. The results of the inversion are good and they track the source range estimate well.

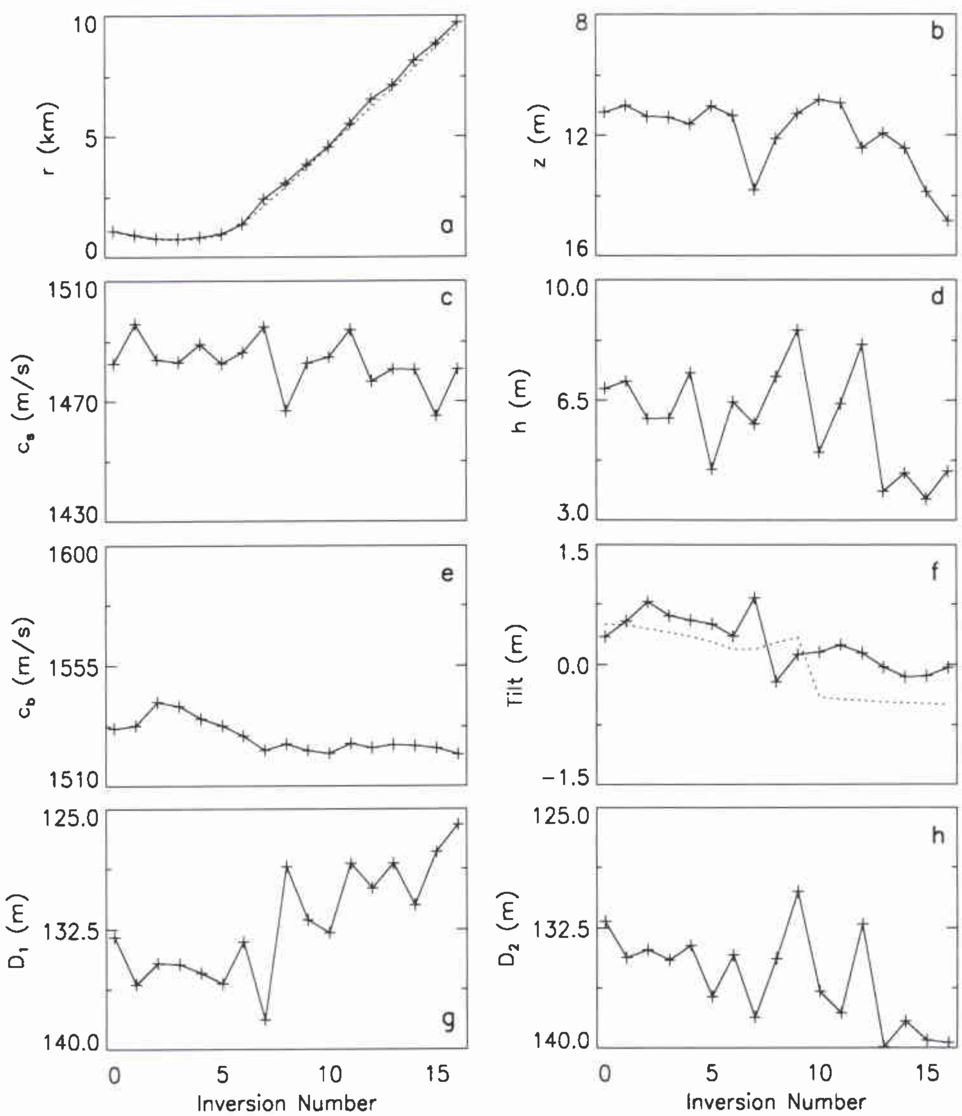

Figure 9 *A summary of the results of the inversions for r, z, c_s, h, c_b, array tilt, D_1, and D_2. In (a) the solid line is the results of the inversions and the dotted line is the approximate range calculated using the ship track and the VLA position. In (f) the dotted line is an estimate of the array tilt using the current data from that time. The zeroth inversion corresponds to pulse 110357, the pulse time decreases as inversion number increases.*

Figure 9 (b-h) are all plotted in the same fashion as (a). The source depth [Fig. 9 (b)] has some fluctuations (thought to be towed at a nominal depth of 12 m) but it is well within the acceptable range for a towed source (i.e., the source will move up and down as the ship changes course or alters speed).

Figure 9 (c) and (d) shows the inversion results for the sediment properties. The results show a lot of variability with range, which actually could reflect the range dependence of the sediment sound speed and thickness. However, it is believed that the variations are due to the instability of the inversion leading to inconsistent inversion results for certain parameters and may also be responsible for some of the outliers.

The basement compressional speed [Fig. 9 (e)] appears to be fairly consistent with range, although there is a slight increase near the array. Figure 9 (f) shows the array tilt, with the exception of two points the tilt is quite stable. The dotted line in Fig. 9 (f) is an estimate of the array tilt calculated using the available current data. The line has been linearly scaled because no information on how currents effect array geometry is available. It seems that the inversion results approximate the estimate well.

The water depths shown in Fig. 9 (g) and (h) proved the difficulty in determining these two parameters, particularly D_2 [Fig. 9 (h)] which corresponds to the water depth at the VLA. This result should be stable since it is the same for each inversion (which is more evidence that the inversion is unstable). The primary source for the inversion instability for the water depths is the low-speed, low-attenuation sediment layer. This sediment layer acoustically appears as part of the water column so it is hard to accurately determine the proper water depth. One final note should be made about this type of plot: Generally it can be somewhat misleading because what appears to be a large change in sediment thickness or source depth is actually occurring over a large distance (> 1 km).

Once the results have been collected it is good practice to go back and compare the pressure fields of the measured and modeled data. For the measured data the source characteristics (including source level) must first be taken out in order to provide a useful comparison. Figure 10 shows the pressure fields in μPa for the measured and modeled data for pulses 102600 and 105557. Pulse 102600 which obtained a mismatch of 0.155 is around 4.5 km away from the source. Pulse 105557 is about 0.84 km away from the source and has a mismatch of 0.33. These results were obtained with the same attenuation in the sediment and bottom as for the synthetic inversion. The two pulses were chosen because they represented the upper and lower levels of mismatch attained, and they were also from two different ranges. For pulse 102600 the structure of the field is matched, but in order to match the levels it was necessary to specify an attenuation of 0.00 dB/λ in the sediment and 0.01 dB/λ in the bottom. This may be a consequence of using the Bartlett processor which normalizes the magnitude of the acoustic field from the inversion or inaccurate source level as a function of frequency used in the calibration of the experimental data.

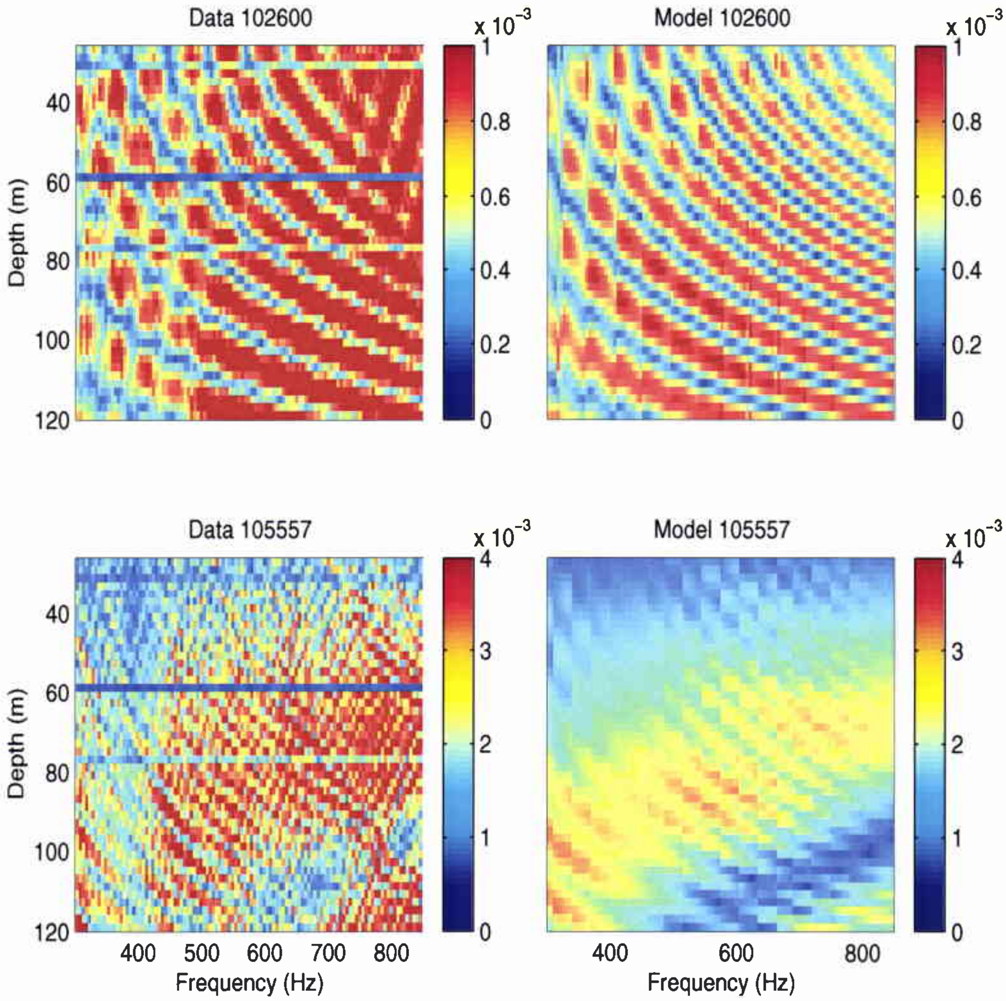

Figure 10 *Plots of the pressure fields in μPa for pulses 102600 and 105557 as a function of depth and frequency. The measured result is on the left the modeled is on the right.*

This can also be seen in Fig. 11 (upper) where the red curve is the measured signal and the green curve is the modeled signal for a mid-water hydrophone.

Notice the band of low pressure level for the experimental data shown in Fig. 10 (lower left) starting around 600 Hz at a depth of 120 m, and extends up to 850 Hz at a depth of around 100 m. This waveguide effect is correctly modeled by **PROSIM** as seen in Fig. 10 (lower right).

Pulse 105557 is a little more complicated because it is close to the source and the source depth is shallow. At this close range the continuous spectrum is still important to the acoustic field because it has not been attenuated. This spectrum is the cause of most of the fine scale structure in the acoustic field. **PROSIM** does not include the continuous spectrum when calculating the acoustic field and therefore will not be able to reproduce the fine scale structure. Therefore, only the large scale structure (the high and low intensity regions) will influence the inversion. This is evident in Fig. 11 (lower) where only the trend of the acoustic field is being matched.

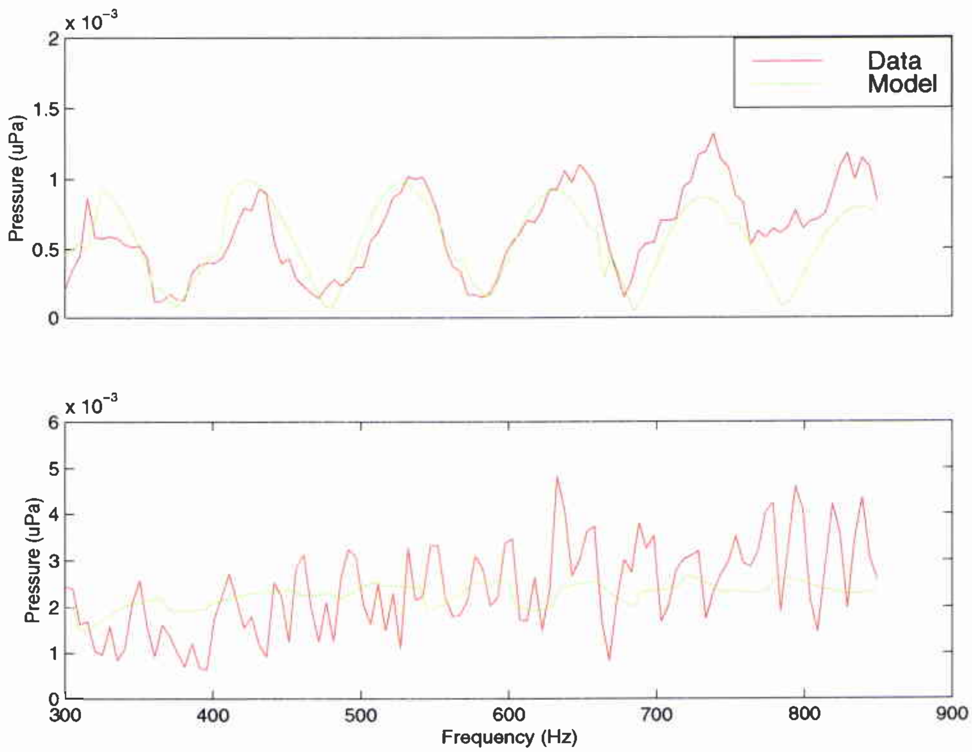

Figure 11 *Plots of the pressure on a mid-water column hydrophone for pulses 102600 (top) and 105557 (bottom). The green line is the inversion result and the red line is the measured data.*

The synthetic inversions showed that a correlation existed between h, c_s, and the water depth. The results of the inversions of the real data also show that the water depths are quite insensitive. Figure 12 illustrates the problems associated with these parameters for pulse 102600. In this case c_b, r, z, and the array tilt were held constant at the values found in the inversion, and D_1, D_2, h, and c_s were varied over their search intervals. The plots are the objective function (Eq. 5) normalized to one with respect to the different parameters. Figure 12 (a-c) shows that D_1 is the least sensitive of these four parameters since for a particular model it can vary up to a third of its search interval and have little to no effect on the objective function. Figure 12 (d-f) show how D_2, h, and c_s are all correlated. Although there are definite minima in these plots, the correlation are still clearly seen as narrow valleys that are not aligned with either parameter axis. Therefore, the parameters can vary over a large range (almost the entire search interval for Fig. 12 (d)) of values and produce the same level of mismatch.

4.2 Comparison with past inversions

The YELLOW SHARK experiments [6, 7] were conducted in the same region near Elba. In both cases inversions were carried out to determine the geo-acoustic properties of the ocean environment. In [6] broad-band inversions were carried out using GA. The range of results found for the different geo-acoustic properties were 5–15 m for h, 1460–1490 m/s for c_s, and 1520–1560 m/s for c_b. Siderius and Hermand [7] inverted sparse broad-band transmission loss data using a simple marching technique. For this inversion the results were 3–6 m for h, 1460–1490 m/s for c_s, and 1550–1585 m/s for c_b.

The results found here agree with the results from the YELLOW SHARK inversions [6, 7] and ground truth data [3]-[5]. The only exception is the c_b found in [7], although the speed is thought to be slightly high [19]. This lends confidence to the SSA inversion and to the repeatability of inversions in this region, since the experiment was conducted in a different season and the inversion was done with a completely new acoustic propagation model and inversion algorithm.

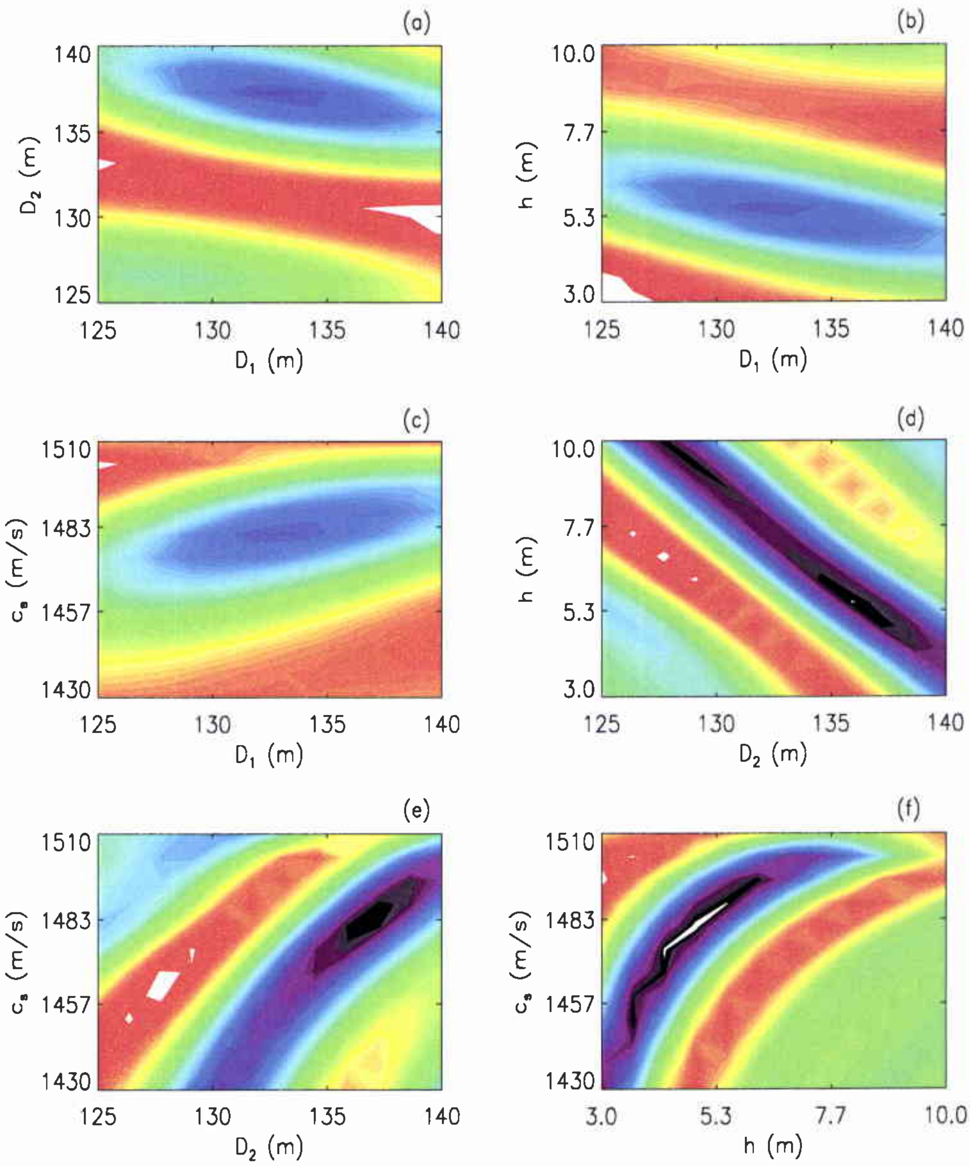

Figure 12 *Plots of the mismatch as a function of D_1, D_2, h, and c_s for pulse 102600. These contour plots illustrate the correlation that exist between the parameters. The blue regions represent low mismatch and the red are high.*

5
Conclusion

In May 1997 SACLANTCEN performed an experiment in the Mediterranean Sea near the Elba island off the west coast of Italy. The purpose of the experiment was to collect environmental and acoustic data in order to validate a broad-band acoustic propagation model. This area was used for the experiment because previous experiments had been conducted in the region, and therefore, a good deal of background information was available. Inversions for geo-acoustic and geometric properties were carried out on acoustic data collected on May 18. A new inversion algorithm, simplex simulated annealing, and the new acoustic propagation model PROSIM were used for the inversion of this dataset.

The range-dependent model was defined by the following unknown parameters: water depth at the VLA, water depth at the source, range and depth of the source, array tilt, sediment thickness, and sediment and basement compressional speeds. The results for all parameters except the water depths were reasonably stable and agreed with the results from previous experiments conducted in the same area.

The water depths proved unstable because the sediment layer had a low compressional speed and a low attenuation (but still much higher than the water column) and, therefore, acoustically it appeared to be part of the water column. This caused a correlation between the water depth and the sediment properties. The sediment properties may have been resolved more uniquely with more accurate bathymetry measurements, which could reduce the search interval significantly (or ideally fix) for the water depth in the inversion.

This work has provided two positive feedbacks, first it was an excellent testing ground for both SSA (which until now had only been used to invert synthetic data) and PROSIM. Secondly it shows that independent experiments can be carried out at different times and produce similar results for a given region. This factor lends confidence to both the inversion techniques and the acoustic propagation models used.

6
Acknowledgments

The first author would like to thank SACLANTCEN for the Summer Research Assistant position that made this work possible. He would also like to extend thanks to the Ocean Acoustics group, and especially Stan Dosso, at the University of Victoria where the simplex simulated annealing algorithm was developed.

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Annex A

SSA IDL code: What to do if...?

The IDL code for SSA is made up of six separate routines SSA.pro, fort.pro, fprosim.pro, amotry.pro, amo.pro, and run.pro. The actual inversion algorithm is contained in SSA.pro. run.pro is a small script file for running the code and is more of a convenience than a necessity. SSA.pro is setup to be "fairly" general, changes to the code can be made with little to no "pain" involved. Some of the most common changes to the code could include:

1) introducing a new acoustic model
2) using a different objective function
3) using a new data set (real or synthetic)
4) inverting for a different set of model parameters.

What follows is a brief description of how to implement these particular changes. The goal has been to produce a code that is as general as possible but this is not always possible. If a problem presents itself and the user can not figure it out please feel free to contact me (Mark Fallat) at mfallat@uvic.ca or my supervisor at the University of Victoria (Stan Dosso) sdosso@uvic.ca.

A.1 Introducing a new acoustic model

This is by far the largest change that can be made to the SSA.pro. In this version of SSA.pro it is set up to run the acoustic model PROSIM. PROSIM requires an input file fort.10 and produces an output file fort.16. The interaction with PROSIM is carried out using the code fprosim.pro. This code is split into four parts, the first runs the code fort.pro which creates the fort.10 input file. The second part spawns PROSIM, the fort.16 output file is read into IDL in the third part. Finally, in the fourth section the objective function is calculated and returned to SSA.pro. SSA.pro only requires the value of the objective function for a given model. Therefore, to introduce a new acoustic model a new code f("new-model").pro needs to be written. This may include writing a new code to produce the input file or altering the existing fort.pro. This code needs to take a set of model parameters in and return a mismatch. The fprosim.pro is called three times in SSA.pro and once in both amo.pro and amotry.pro so the f("new-model") will need to be added in these places as well. It is good practice to run some synthetic inversions once a new acoustic model has been introduced. This way the user can determine if everything is working well.

A.2 Using a different objective function

SSA.pro is set up use the Bartlett processor summed coherently in depth incoherently in frequency. If a new objective function is wanted (or needed) the only changes that are needed are in fprosim.pro. If the new objective function requires something other than complex pressures then changes must also be made to the measured pressure vector ("ptrue") in SSA.pro. This is not a difficult change but some care must be taken to ensure that the measured and modeled pressure (modeled pressures are the "prep") vectors agree.

A.3 New data (real or synthetic)

Running inversions with new data real or synthetic is quite an easy change. In SSA.pro the measured pressure vector ("ptrue") must be changed to accommodate the new data. In this case the user should take care to make sure that there is agreement between the "pture" and "prep" vectors.

A.4 Inverting for a different set of parameters

There are several things that need to be changed when a new set of parameters is being inverted for. The first (and most easily forgotten) is the number of unknown parameters. This is the variable "dim", in SSA.pro, which is very important because the simplex uses $N+1$ models in an N dimensional space, so the N must be defined. The second change is to the search bounds "minlim" and "maxlim" and the starting model "start". The final change is to the fort.pro file (or whatever user designed file creates the input file) where the new parameters are put into the input file.

It is possible to need more then one of these changes at once. The best advice to the user is to make changes one at a time. Therefore, there is the least chance of forgetting something. The information given here is just a brief outline of what to look for when changing the code. The user is expected to have at least basic understanding of IDL (or MATLAB) coding in order to implement these changes.

Document Data Sheet

Security Classification		Project No.
UNCLASSIFIED		03-A
Document Serial No.	**Date of Issue**	**Total Pages**
SM-332	July 1999	31 pp.

Author(s)

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Title

Geo-acoustic inversion of the PROSIM'97 experimental data using simplex simulated annealing.

Abstract

In the spring of 1997 SACLANTCEN performed an experiment near the Elba island in the Mediterranean Sea. The PROSIM'97 experiment was designed for the validation of a broadband acoustic propagation model. During the period of May 15-23 of 1997 both environmental data (i.e., sound-speed profiles, current measurements, temperature profiles, etc.) and acoustic data were collected. The data were collected from a well-known area where previous experiments have been performed. This report describes the geo-acoustic inversion applied to some of the acoustic data from this experiment. Estimates of the seafloor properties and the experimental geometry were determined from broadband acoustic pressure fields. The inversions were carried out using a new hybrid global optimization algorithm (simplex simulated annealing), and a new and fast acoustic propagation model PROSIM. A description of the inversion algorithm is given and the results of the inversions are presented and compared to past inversion results for this region.

Keywords

Geo-acoustic inversion – efficient broadband propagation model PROSIM – hybrid inversion algorithm – simplex simulated annealing

Issuing Organization

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Report no. changed (Mar 2006): SM-332-UU

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