GEOPHYSICAL SEAFLOOR EXPLORATION WITH A TOWED ARRAY IN SHALLOW WATER

Sergio M. Jesus

UCEH - Univ. do Algarve
Campus de Gambelas
PT-8000. Faro, Portugal
e-mail: sjesus@ualg.pt

Andrea Caiti

DIST, Univ. of Genova
via Opera Pia 13
16145 Genova, Italy
e-mail: andy@dist.unige.it

Abstract. The quantitative measurement or estimation of the geophysical properties of the seafloor upper sedimentary strata is a requirement in several marine applications, from geotechnical engineering to underwater acoustics. Traditional methods employ in-situ instrumentation (cone penetrometers, coring, etc.) and are able to probe the seafloor at selected points. This project aims at exploring the feasibility of seafloor model identification by acoustic means. In particular, the project has considered the use of an acoustic system, in which a ship tows both an acoustic source and an horizontal array of receivers. From the acoustic field measured at the receiving array, the seafloor parameters are estimated by suitable inversion algorithms. The project focused in particular on the use of such a system in shallow waters, and considered the advantages and limitations of the method from the point of view of system requirementes, signal processing and inversion strategies. Sensitivity studies show that it is indeed possible to recover the seafloor parameters in shallow water with a moderate aperture towed array, and experimental results are shown to demonstrate the feasibility of the concept. Possible improvements and further lines of research are also discussed.

1 Introduction

Estimating the seabottom geophysical structure from the analysis of acoustic returns of an explosive source (air-gun, sparker, ...) has been used for a long time as a routine survey technique. However, in order to get a precise quantitative picture of the seafloor upper strata, such techniques have to be complemented with in-situ measurements at selected locations (as coring, grab samples, etc.). In-situ measurements are expensive and time-consuming, and are one of the major drawback of conducting wide area surveys in shallow waters, where bottom variability is much greater than in deep water.

This project has the goal of investigating the feasibility of a quantitative estimate of seafloor geophysical/geoacoustic parameters (compressional and shear velocities and attenuations, density, ...) by using only acoustic remote sensing techniques. In particular, the project is concerned with the use of ship-towed instrumentation, that, if shown succesfull, will allow seafloor properties to be estimated from a moving ship in a survey fashion. Moreover, wide areas could be covered in a much smaller time than that required with present techniques, and also the surveys could easily be repeated, if needed (for instance, in estuarine areas with consistent sediment transport), due to the reduction in costs provided by the remote acoustic technique.

The main idea of the project is that of inverting the acoustic field produced by a known source and measured at a receiving array in order to identify a physical seafloor model. Such general techniques are referenced in the literature as "full-field" inversion methods (see [1] for an up-to-date reference on the subject), and owe their difference from more traditional seismic or tomographic inversion strategies from the exploitation of the entire structure of the acoustic field, and not only time of flight, amplitude vs. offset, etc. In this respect, full-field inversion schemes can be regarded as an extension of the Matched Field Processing (MFP) technique [2] to the sensing of environmental parameters, and one may also refer to them as Matched Field Inversion.

The feasibility of the full-field or Matched Field inversion idea has been demonstrated both theoretically and experimentally for certain source-receiver configurations. In particular, long aperture synthetic horizontal arrays [3] or vertical receiving arrays spanning the whole length of the water column [4] have both been shown to produce reliable estimates of bottom properties in shallow water. However, both techniques require the use of fixed instrumentation, generally moored at the seafloor, and are not practical for wide area surveys application.

The experimental configuration considered in this project is more apted to survey applications, but is much more challenging from the point of view of bottom model identification. A ship towing an acoustic source and an horizontal array of receivers is considered. The system is explicitly required to be used in shallow water: this poses some constraints on the possible array aperture, since a long array towed in shallow water may face some risks during navigation (for instance, may be severely damaged if the towing ship has to stop or abruptly change course during an emergency). The constraint on array aperture poses a major scientific question: is it possible, and with what limitations and conditions, to estimate the seafloor parameters from a small to moderate aperture towed array? The research described in this report gives an answer to the question, considering both computational and experimental aspects, and leading also to recommendations for experimental design and instrumentation requirements. In particular, we will show with simulated and experimental data how it is indeed possible to successfully estimate bottom properties in shallow water by inversion of the acoustic field measured at the towed array. A key point for the success of the technique is the precise monitoring in time of the position of each element in the receiving array

There are several aspects that have to be taken into account in fully describing the achievements of the project. These are shortly listed below, and to each one of them is devoted a section in the following:

- system limitations and requirements (array aperture, source frequency, accuracy in the geometry determination, etc.);
- inversion strategy (data processing, cost function selection, global search algorithm);
- experimental design, including ground-truth techniques and comparison of results.

Depth	P vel.	S vel.	P att.	S att.	Dens.
(m)	(m/s)	(m/s)	(dB/λ)	(dB/λ)	(g/cm^3
0.0	1500	0.0	0.0	0.0	1
140.0	1550	130	0.1	1.7	1.49
145.0	1700	350	0.8	2.0	1.88
150.0	2500	900	0.01	0.01	2.4

Table 1: Canonical environment

A last section will discuss some open problems in the development of this technique, some possible improvements and some future extension of the whole concept. We want to emphasize, at this stage, that both the theoretical analysis and the data inversion strongly rely on the availability of acoustic field computational codes that are both accurate and fast. In particular, in this work we have employed the code OASES, a more recent version of SAFARI [5], developed by the same author.

In the following, we will also try to avoid, up to a certain extent, a detailed formal justification of some of the results obtained. When needed, the reader is referred to more specific publications appeared in the scientific literature.

2 System requirements

The experimental configuration that we want to investigate is as follows: the survey ship tows at the same time, on two independent cables, an harmonic acoustic source and an array of recivers. The nominal depths of both source and receivers, as well as the (nominal) source-recivers distance and the transmitted frequency(ies) can be chosen and can vary from one survey to another. In order to determine the expected performance of the system, specify the instrumentation requirements, and draw some conclusions on the system operation, the following procedure has been adopted: a matched-field-like objective function has been determined, and the sensitivity of the correlation maximum with respect to array length, source depth, receiver depth, source range, sensor noise, source frequency and frequency band has been investigated. In this simulative study, a canonical case has been considered, where the receiving array consists of 64 hydrophones, 4m spaced, towed at 100m depth, an harmonic source at 100 Hz is also towed at 100m depth and at a range of 200m from the first hydrophone on the array. The canonical environment, whose parameters are reported in Table 1, is formed by an homogeneous 140m depth water layer overlying a relatively soft bottom consisting of two 5m thick layers and a hard halfspace at 150m depth (with respect to the water surface).

2.1 Data model and the conventional matched filter

The deterministic sound pressure at the receiver location r_l, z_l is modeled as the solution of the wave equation for a narrowband point source exciting a horizontally stratified range-independent fluid-elastic environment, that is the Green's function inverse zero-order Hankel transform:

$$p_l(\omega_k, r_l, z_l, z_o; \gamma) = \int_0^{+\infty} g(\kappa, \omega_k; \theta_l, \gamma, z_o) J_o(\kappa r_l) \kappa d\kappa \tag{1}$$

where l denotes the lth array sensor, ω_k is the kth frequency bin, z_o is the source depth and γ is a vector containing all the pertinent environmental parameters under estimation. Thus, at time snapshot n, the acoustic pressure field received by an array of L sensors can be modeled as a multivariate complex normally distributed random variable:

$$\mathbf{y}_n(\omega_k, \gamma_T) = b_n(\omega_k)\mathbf{p}(\omega_k, \gamma_T) + \epsilon_n(\omega_k), \quad k = 1, \cdots, K \tag{2}$$

where ϵ is the sensor noise assumed to be zero mean and uncorrelated both in time and from sensor to sensor. The scalar b_n is a complex random variable that accounts for the nondeterministic amplitude variation at the receiver due to the environmental inhomogeneities and fluctuations that are not included in the sensor noise. Subscript T denotes the true value of the parameter under estimation.

Function (1) being known for each given γ, the problem is to detect a known signal $\mathbf{p}$ in white noise, whose optimal solution is given by the well known matched filter. Let:

$$\Phi_{CMF}(\omega_k, \gamma) = \mid \mathbf{p}(\omega_k, \gamma_T)^H \mathbf{p}(\omega_k, \gamma) \mid^2, \quad \gamma \in \Gamma \tag{3}$$

be the matched filter output based on model replica prediction $\mathbf{p}(\omega_k, \gamma)$ for the search parameter γ, with Γ denoting the whole environmental search space, and the superscript H denoting Hilbert transpose. Thus, the broadband optimal estimator $\hat{\gamma}_T$ of γ_T is given by:

$$\hat{\gamma}_T^{CMF} = \arg\max_{\gamma} \frac{1}{K} \sum_{k=1}^{K} \mid \sigma_s^2(\omega_k) \mid^2 \Phi_{CMF}(\omega_k, \gamma) \tag{4}$$

where $\sigma_s^2(\omega_k)$ is the source power at frequency ω_k. We note that the conventional matched filter (CMF) is *not* the only estimator that can be considered. In particular, also the broadband maximum likelihood matched field processor (BBML) and the matched filter in the wavenumber space (WS-CMF) have been investigated. For a detailed discussion the reader is referred to [6], [7].

2.2 Sensitivity study

The rationale for the sensitivity study is the following: the estimate of $\hat{\gamma}_T^{CMF}$ will be more accurate the sharper the peak (correlation level) in the matched filter output Φ_{CMF}, i.e., the more sensitive Φ_{CMF} is with respect to the bottom parameters. Moreover, the estimate will be less ambigous if the matched filter output has less (or possibly none) local maxima (sidelobes). By sistematically varying the system parameters (array length, source frequency, etc.), one can get a picture of the behaviour of the system with respect to the identification of the various parameters. As an example, in Figure 1 the output of the conventional matched filter is shown for different choices of the array aperture and for the compressional and shear velocities of the canonical environment. This sistematic study has lead to the following conclusions:

- *Array aperture:* varying the array aperture from 63m up to 2016m produces an increase on bottom parameter sensitivity. This increase is very steep for array apertures smaller than 250m, and then there is a saturation effect where a further increase of aperture does not give any substantial sensitivity gain (see Figure 1).

- *Frequency:* varying the source frequency between 25 and 200 Hz changes the signal penetration into the bottom. An increase of frequency improves the sensitivity

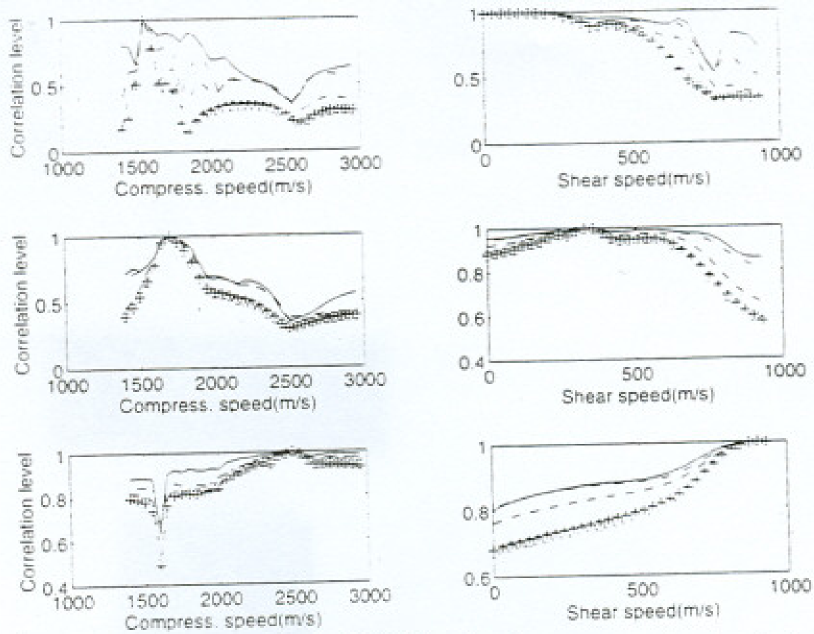

Figure 1: Array aperture test with the CMF function for compressional and shear velocity parameters. First bottom layer on the top and deepest layer on the bottom. Array aperture of: 63m (- solid), 126m (-.- dash-dot), 252m (– dashed), 504m (.. dotted), 1008m (++), and 2016m (oo).

to compressional parameters, although the improvement vanishes at deeper layers. Shear parameters showed a higher sensitivity at lower frequencies, that provided also smoother curves (less sidelobes effects) and so a higher potential for unambiguous inversion. As a rule of thumb, one can consider that, with a given frequency, bottom parameters down to one wavelength into the seafloor can be recovered, with a definition of one third of a wavelength.

- *Bandwidth:* varying the source bandwidth between 2 and 60 Hz (central frequency still fixed at 100 Hz) does not increase significantly the sensitivity, but produces smoother objective functions, at the expense of a much larger computational effort.

- *Source-receiver positions:* changing relative source-receiver depth changes the sensitivity according to the higher or lower transfer of energy between source and receiver that is depending on mode excitation vs. depth. That is highly dependent on the particular environment chosen for testing. Changing source-receiver range has a similar behaviour depending on the modal interference pattern vs. range. In both cases placing the source and the array at high energy transfer locations improves sensitivity.

- *System parameters mismatch:* as expected, it has been found an higher dependence to depth than to range mismatch. The accuracy to which sensor depth has to be known has to be better than $\lambda/5$, being λ the wavelength, while an accuracy of $\lambda/3$ will be enough for sensor range.

- *Signal to noise ratio:* the comparison has been made between CMF, BBML and WS-CMF. The BBML provides better defined maxima at SNR = ∞, while at SNR

= 10 dB all estimators showed similar performances. Decreasing SNR shows that the CMF is the more robust keeping a constant performance down to -5 dB.

3 Inversion strategies

The inversion of a highly nonlinear expression such that relating the bottom parameters with the acoustic pressure field on a complex shallow water environment requires the optimization of a multidimensional ambiguity surface. The shape of the surface is in general unknown, but suspected to have several local maxima, thus inhibiting the use of classical gradient-based search methods.

Two strategies for determining the inverse solution have been investigated: an adaptive genetic algorithm (GA), and a neural network-like approach based on the approximating properties of gaussian Radial Basis Functions (RBF).

3.1 Adaptive GA

Global search optimization techniques avoid the exhaustive search of the whole parameter space (computationally prohibitive), while mantaining the ability of escaping from local maxima. Among the possible global search strategies, GA have demonstrated significant potential [8]. In the following familiarity with the GA machinery and GA jargon is assumed. The implementation used follows very closely that proposed in [9], except for the selection of the "new" population at each iteration. The algorithm described in [9] gives to each member of the "old" population a chance of reproduction. It has been found, in our case, that this procedure slows down convergence, and leads to very long computation times before producing reasonable estimates. Instead, a procedure allowing reproduction of individuals only above a certain fitness has been implemented, ensuring a faster convergence. In order to avoid the risk of finding only a local maxima, the probability of mutation has been increased above the values normally used by GA practitioners. Also, an adaptation of the search space interval has been introduced: after a certain number of iterations (for instance, every ten iterations), the search space is restricted to the interval that contains 95% of the current population. Simulation results have shown that the adaptive GA is able to produce better results with respect to the non adaptive version [6]. The price paid is that any interval reduction criteria introduces a potential risk of missing the true parameter value.

3.2 RBF approximation

The idea of the RBF approach is to find a global approximation of the inverse function by means of a series of Radial Basis Functions, and in particular, to ensure continuity and smoothness of the inversion, of gaussian functions. The RBF method does *not* belong to the class of of global search strategies (as, for instance, simulated annealing), that tend to exhibit the same merits and drawbacks of GA. For this reason it may be considered a valuable alternative, or a complementary approach, to the GA-based inversion.

A complete formal description of the RBF-based inversion can be found in [10]. Roughly speaking, the RBF method relies on the idea of determining an approximation of the inverse function in the form of a series expansion, where the basis functions take the form of gaussian or gaussian-like functions. The coefficients of the series are determined from a set of known input-output relations ("training set"), generated, for instance, through forward model computations. In the present situation, the "input" is the acoustic field measured on the towed array, and the "output" is the corresponding vector of seafloor parameters. If the training set is generated in such a way to cover most of the significant physical situations, the resulting series expansion will be a smooth approximation of the nonlinear inverse function on its global domain. The computational burden of the RBF method is mainly in the generation of the training set, while the computation of the solution from the measured data can be performed, once the series coefficients are identified, in real time.

The accuracy of the RBF approximation must be evaluated in terms of ensemble errors over a set of cases ("test set") spread over the whole seafloor parameters domain, since we want to test the approximating abilities on the large, and not just locally. Typically, a training set of 800 input-output cases has been employed, by randomly selecting the bottom parameters in the search space interval. Another set of 50 cases (not included in the training set) has been generated, and the acoustic field has been fed to the RBF expansion, that generated the corresponding seafloor parameter estimate.

Typical results have led to a mean error in compressional velocity retrieval between 1 and 3% (depending on the layer), while the shear velocity mean error is of the order of 20-25% for all layers, comparable to those of the adaptive GA.

No cases were found where one of the two inversion methods was clearly preferable to the other.

4 Experimental results and comparison with "ground truth"

From the simulative studies briefly reported in the previous section, it appears that one of the critical aspect that has to be taken into account for a successfull application of the method is the *precise monitoring of the source-receiver geometry.* One of the major concern, in this respect, is the behaviour of the towed array. In principle, a neutrally buoyant towed array, with homoeneous density, stays horizontal when towed at constant speed. In practice, due to non perfect buoyancy effects, perturbation in the ship speed due to the sea state, etc., the ideal situation is very seldom encountered. Hence, one of the major efforts of the project has been in determining and installing a system to measure, in real time, the movement of the receiving array. This system, and its operation, is described in the next subsection.

In order to test the whole method in a realistic situation, an experiment has been conducted, in the period February 25 - March 4, 1994, at one site at the Adventure Bank, SW of Sicily, in the Mediterranean Sea, with the R/V Alliance. At this site a complete set of towed array data and "ground truth" measurement has been obtained. The ground truth data and the preliminary results on the inversion of towed array data are described in subsections 4.2 and 4.3.

4.1 Monitoring the towed array position

In monitoring the array position with respect to the source, we have split the problem in two parts: one is the determination of the distance between the source and the first hydrophone on the receiving array, the other is the monitoring of the position of the whole chain of receivers with respect to the first one. Note that the source depth was

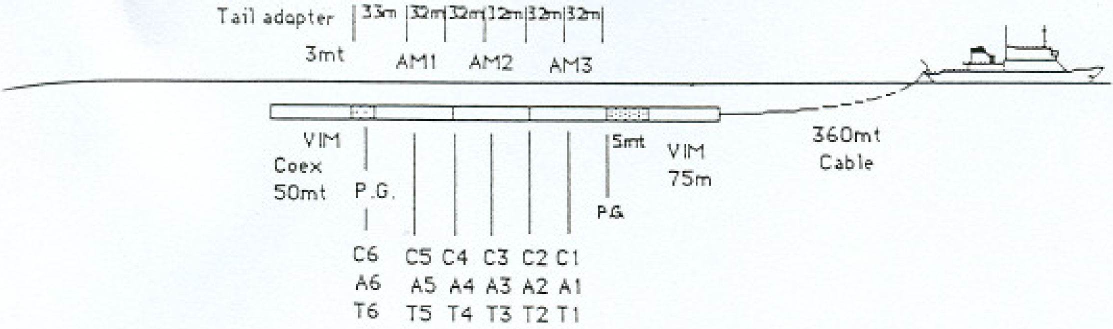

Figure 2: Towed array with position monitoring sensors. T stands for tiltmeter, C for compass, A for accelerometer, P.G. for pressure gauge

measured with a pressure gauge installed on the source. The first part has been addressed acoustically: the source was periodically switched from cw mode to the burst mode; in burst mode a sharp acoustic impulse was transmitted and the distance source-first receiver is determined from the time of flight of the pulse. The second part has been addressed with the use of non-acoustic sensors, that allow to monitor at each time instant the movement of the array without interfering with the acoustic data acquisition.

In particular, a set of sensors has been purposely installed on the acoustic array, consisting of pressure gauges, tiltmeters, compasses and accelerometers. In Figure 2 the position of these sensor packages is reported. A data acquisition system for the non acoustic sensors was also designed and installed on board the platform, independent from the acoustic acquisition system. The system allowed to monitor in real time the movement of the array during the experiment runs.

Through the non acoustic sensors, it has been possible to observe that, during the experiment, the array was never straight nor horizontal. In Figure 3 a series of snapshots, taken over a period of 5 minutes, of the estimated array depth are shown. Note that not only the array is not horizontal, but it also shows a small oscillatory behaviour. Although small, this behaviour is such that the variations in depth from one array position to another is in certain cases greater than the limit of $\lambda/5$ (approximately 3m at 100 Hz) that has been determined by the sensitivity study. It is then clear that a monitoring system as the one designed and installed is a critical necessary condition for the success of the method.

4.2 Obtaining "ground truth" information

To evaluate the performance of the method proposed, it is necessary to have available an independent measurement of the same geophysical properties that are estimated with the acoustic system. One of the problems in getting independent measurements is that one has to use more traditional techniques that exhibit all the kind of drawbacks that the proposed method wants to avoid.

The following procedures were adopted:

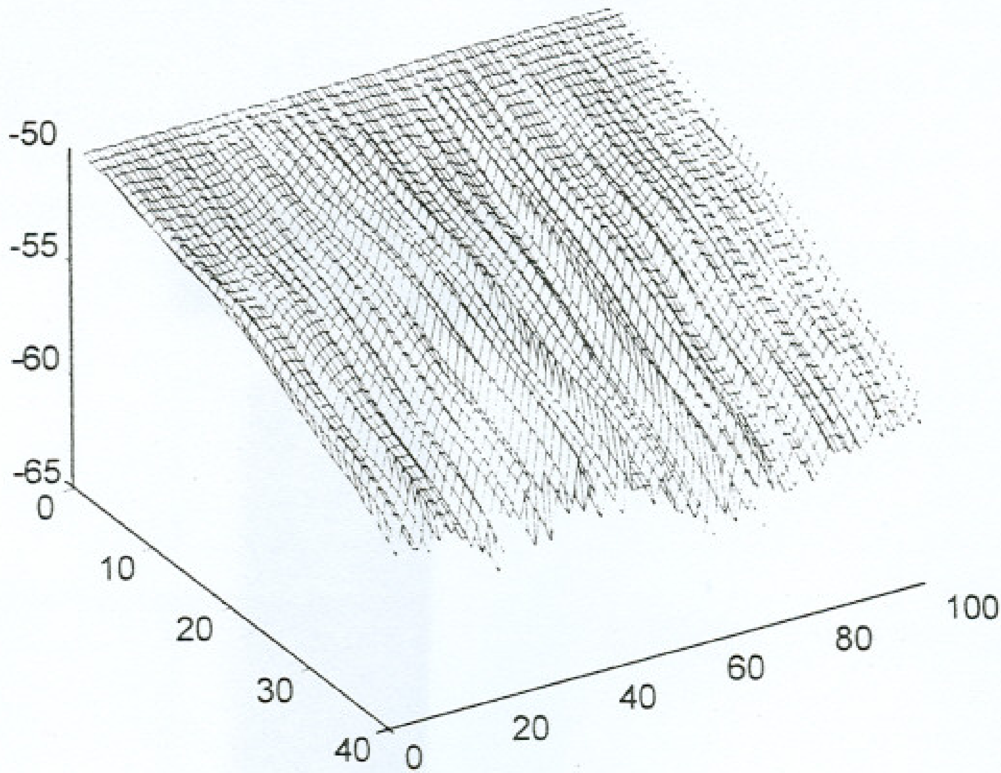

Figure 3: Array movement vs.time. Z-axis is depth (m) from the water surface, X-axis is snapshot number (100 snapshot corresponding to five minutes). Y-axis is hydrophone number (the array has a total of 40 hydrophones).

- *Seismic survey:* conducted by towing at the same time along the tracks selected a 3.5 KHz boomer and a 5000 J Sparker. It gives a qualitative image of the seafloor and of the fine layering structure;

- *Coring:* three gravity cores were taken along the selected track, reaching at most a depth of 1.25m. The cores have been afterwards analyzed in the laboratory, and values of grain size, density, porosity, compressional wave speed, calcium carbonate content obtained. As a general description, the bottom can be considered mostly composed by carbonate sand.

- *Seismic interface waves:* in order to measure the shear velocity as a function of depth, an array of geophones has been deployed at the seafloor, and the dispersion characteristics of seismic interface waves excited at a relatively short distance (1000m) have been measured. From the dispersion curves, the shear velocity has been estimated with the technique described in [11].

The shear wave velocity measurement has been obtained at the same site of one of the cores. By using Hamilton's correlation tables [12], it has been possible to build a so-called *generic* geoacoustic model for the site. By correlating this model with the seismic survey, and taking into account the known geological information on the site, the geoacoustic model can be extended to the whole experimental track. In Figure 4 the generic geoacoustic model is superimposed to the seismic line and to a geological interpretation. Note that the velocities obtained, both compressional and shear, can be considered low for a sandy bottom.

4.3 Acoustic data processing and inversion results

The inversion of the acoustic data is not yet completed at this stage (May 1995), however some significative results have already been obtained. The inversion attempts so far have been concentrated on the use of the RBF approach, so no results are reported for the adaptive GA scheme.

During the experiment runs, the acoustic source was transmitting harmonic signals at different frequencies simultaneously. The choice of the frequencies transmitted was made on board by compromising with the desired frequencies determined *a priori* in simulations and the ambient noise measured during the runs. The array used in the experiment consisted in 40 hydrophones, 4 meter spaced, for a total aperture of 156m. The same track has been surveyed several times and in different days. The results presented in the following have been obtained from a single run and with 110 Hz data. The source-first receiver distance for the run considered has been estimated in 545m.

One of the first problem that have to be addressed by the RBF method is that, due to the variability in the towed array position, and since the geometric information have to be used in the generation of the training set, is not possible to use the same training set for the whole data. On the other hand, is not feasible to produce a single training set for each acoustic field snapshot. A compromise has been obtained by partitioning the set of geometric positions of the array in homogeneous clusters, where the difference in depth between corresponding hydrophones in the same cluster is at most 2m. i.e. whithin the prescribed $\lambda/5$ tolerance. For each of the clusters (5 for the run considered) a training set is generated, and an approximate inverse function is built. The layering of the bottom strata is fixed *a priori* with the rule of thumb of $\lambda/3$ thickness, so the thickness *is not* an

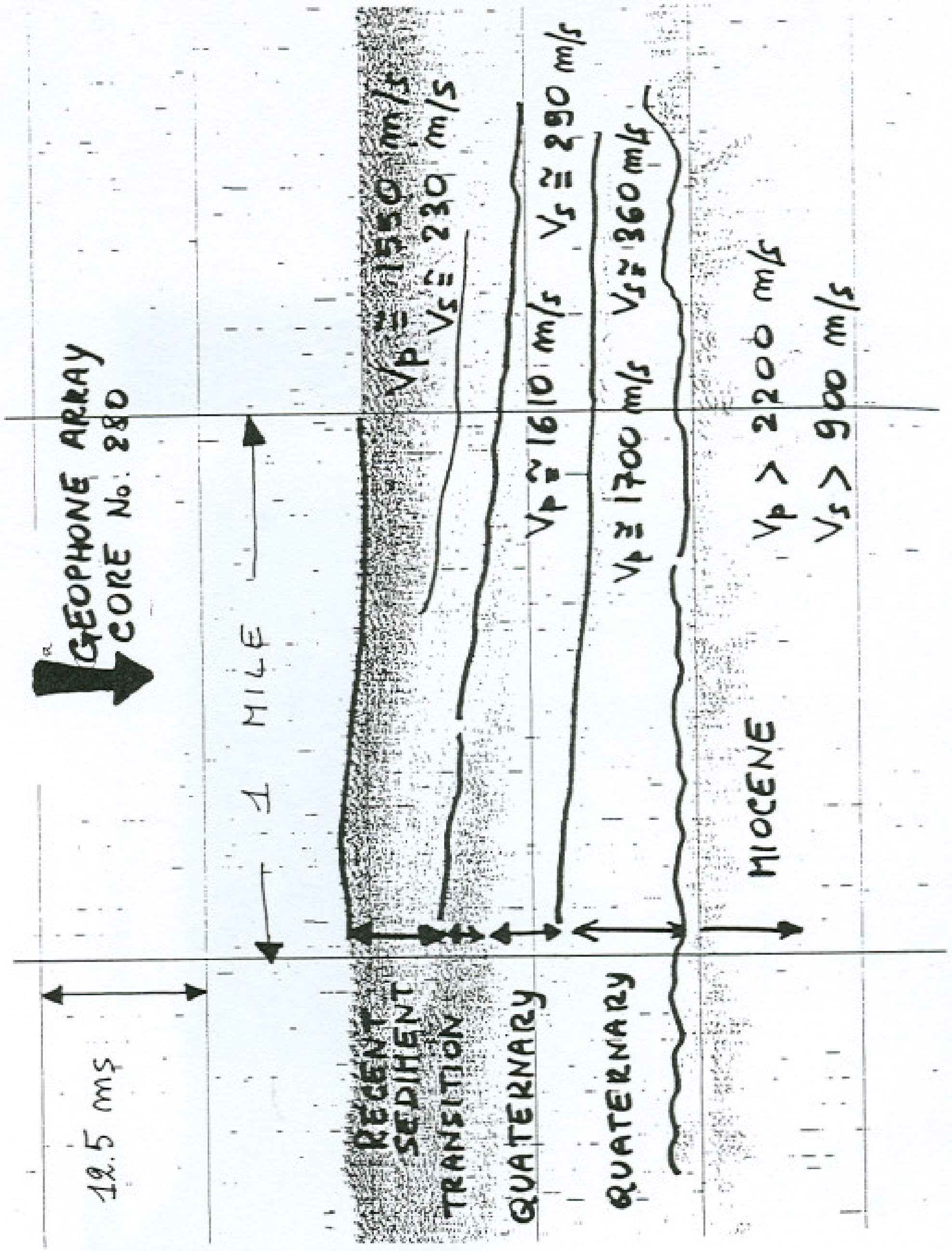

Figure 4: Portion of the seismic survey (Boomer) along the towing track, and comparison with the generic geoacoustic model and the geological interpretation

Thickness	P vel. mean	P vel. std.	S vel. mean	S vel. std.
(m)	(m/s)	(m/s)	(m/s)	(m/s)
0 - 4.5	1576	30	184	142
4.5 - 9	1660	86	353	140
9 - 13.5	1850	73	373	154

Table 2: Inversion results. Velocity values are obtained by averaging the inversion results over a range of 600m. Standard deviation is also reported.

unknown of the inversion. The measured acoustic field is then input to the RBF inverse to obtain the estimated geoacoustic parameters.

Before feeding the data to the inverse function, a smoothing of the data has been performed. In particular, it was noted that, at least for the run reported here, there was variability in the data that was not conceivably due to the variability in the environmental parameters. By applying a 4 points moving average to the data a more stable behaviour of the field was noted, still preserving the structure of the field.

In Table 2 we report the estimate obtained with the data of a single cluster at 110 Hz averaged over a range of 600m, in a position along the survey line approximately half of a mile leftmost with respect to the coring location (see Figure 5).

In commenting these preliminary results, we note that they are close to those of the Hamilton-like geoacoustic model, with a constant bias toward higher velocities. On the other hand, these values are closer to what may be expected for a carbonate sandy bottom (in this discussion, one has also to remember that in the Hamilton tabulations most of the sandy areas were characterized by silicaeous sand). However, before claiming the success of the experiment, we note also that there is a notable variability (reflected in the standard deviations) in the results obtained by inverting every single "snapshot" of the acoustic field. Whether this is a true physical effect or a sign of poor stability behaviour of the RBF inversion we are not yet able to assess.

5 Conclusions

The results and achievements obtained in the first two and a half years of the project have been reported and briefly discussed. Although not all the data have yet been processed at this stage, the preliminary results allow to conclude that acoustic remote sensing of seafloor geophysical properties with a towed array in shallow water is feasible and can lead to success. One of the key aspects for use of such a system is the precise measurement of the array motion at any time instant. A possible solution to this problem has been designed and installed in an existing operating array by means of non-acoustic sensors. In this way there is no interference among the acoustic data acquisition and the position monitoring.

The idea underlying the project discussed here can be further extended: in particular, it is now realistic to state that seafloor models can be identified by inverting the acoustic field as measured by a set of randomly placed sensors, as long as the geometry of the source(s)/receivers configuration is known and constantly monitored. This opens up the opportunity of using autonomous receivers (for instance, suonobouys) and even noise sources of opportunity (commercial ships in transit), totally eliminating the need of a ship to conduct the survey, with the consequent reductions in costs. Positioning of each receiver station may be determined combining GPS information with non-acoustic sensors.

Acknowledgements

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