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Through-the-sensor geoacoustic inversion along a towed horizontal line array – results from real data set in the Mediterranean Sea

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THROUGH–THE-SENSOR GEOACOUSTIC INVERSION ALONG A TOWED HORIZONTAL LINE ARRAY – RESULTS FROM REAL DATA SET IN THE MEDITERRANEAN SEA

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Abstract: *The assessment of active sonar performances in shallow water strongly depends on the environmental conditions. Of most importance, bottom properties are known to strongly affect the forward acoustic propagation and reverberation fields. It is thus essential that reliable geoacoustic models of the seabed be available in a given area so that sonar performances can be estimated with a reasonable level of confidence. In the past decade, several dedicated geoacoustic inversion methodologies have been proposed. Based on experimental set-up's that "probe" the environment in a similar manner to the one of sonar systems (in terms of used devices and geometries), they aim at assessing a set of seabed parameters that allows to replicate the impact of the true seabed on the acoustical field emitted by a sonar. This paper focuses on the so-called through-the-sensor (TTS) geoacoustic inversion approach that is based on the inversion of acoustical data along a towed horizontal array with matched-field processing techniques. Obviously oriented toward an integration onboard operational low frequency active sonar chains, proofs of the relevantness of that concept have already been shown in the past. Moreover, it has also been demonstrated that such an approach is promising for handling the challenging case of range dependent environment. Here, TTS inversion results with acoustical signals that span the same frequency band of present operational LFAS (800-1800 Hz) are presented. The methodology is applied along a known site Southward the Sicily Island (Malta Plateau) with experimental data.*

Keywords: *Geoacoustic inversion, through-the-sensor, matched field*

1. INTRODUCTION

The assessment of active sonar performances in shallow water strongly depends on the environmental conditions (water column, sea surface and seabed). So far, considerable attention has been paid to develop methodologies for estimating the associated environmental parameters. Of most importance, bottom properties are known to strongly affect the forward acoustic propagation and reverberation fields. During the past decade, the geoacoustic inversion techniques have been shown to provide a set of popular methodologies that can provide relevant information of the seabed properties usefull for improving the evaluation of sonar performances. Directly integrated within an active sonar system (ie. when solely using the acoustic sensors of a given sonar system), they have given rise to the "through-the-sensor" (TTS) concept as the acoustic measurements and the predictions are linked to the same sonar. Among the proposed geoacoustic inversion methodologies, the use of towed horizontal line array together with a low frequency active sonar (LFAS) has been presented as a way to handle the difficult case of range dependent environment [1][2][3].

This paper considers the application of this approach with a data set that the NATO Research Center (NURC) acquired during the BASE'04 experiment with an LFAS system whose design is close to standard operational systems.

2. OVERVIEW OF THE BASE'04 EXPERIMENT

In April-May 2004, the NURC conducted the BASE'04 experiment Southward the Sicily Island in the Mediterranean Sea at three different locations: Malta Plateau, Adventure Bank and Medina Bank. One of the goals of the experiment was to acquire acoustical data sets that would allow to test the TTS approach. The present paper only focuses on the Malta Plateau track. The interested reader is invited to read a companion paper [6] presented in the same proceedings for complementary results along the other tracks.

1s-linear frequency modulated sweeps from 800-1800Hz generated by a towed acoustical source (with vertical aperture around ±35 ° at -3dB) were repeated every 60s and recorded along a towed horizontal array (HLA). The array is a cardioid one with 84 triplets equidistantly spaced 42 cm. In this study, only 1 line of the array has been considered with a limited subset of hydrophones (either 21 hydrophones or 5 hydrophones) . Both source and HLA were towed at around 60 m depth and horizontally separated by around 320m.

3. INVERSION METHODOLOGY

The integrated inversion package SAGA [4], based on genetic optimization algorithm has been used for this work. Due to the relatively high frequency of the acoustical signals, SAGA was employed with the GAMARAY [5] ray model as the core forward acoustical model. As an important matter of fact, the short separation between the source and the receivers (few hundreds of meters) allows to proceed to range-independent inversion. This provides an efficient inversion tool that allows to perform geoacoustic inversions within reasonable time-frames. The algorithm looks for a set of model parameters that minimizes a cost function that measures the mismatch between measured and modelled acoustical data. For this work, the mismatch was mainly based on the Bartlett processor coherent in frequency and summed incoherently over the receivers given in Eq.(1):

$$\phi = 1 - \frac{1}{N_r} \sum_{j=1}^{N_r} \frac{\left| \sum_{i=1}^{N_f} p_{ij}^{*} q_{ij} \right|^2}{\sum_{i=1}^{Nf} \left| p_{ij} \right|^2 \left| q_{ij} \right|^2}, \tag{1}$$

where N_r is the number of hydrophones, N_f the number of frequencies, p and q respectively the measured and simulated complex pressure fields along the array.

The inversion algorithm was parametrized in order to simultaneously invert for the geometrical parameters of the experiment (depths of the source and the first receiver, tilt of the array, water depth and source–receiver horizontal separation) and the geoacoustical parameters (compressional speeds, attenuation, density and thickness of the sediment layer or the basement).

4. MALTA PLATEAU TRACK INVERSION RESULTS

The Malta Plateau track was designed along a well known site for which groundtruth data have been acquired over several past experiments (see [2] and references herein). It is characterized by an important range dependency of the sedimentological properties. As shown on the seismic profile presented in Fig.1, the sediment is composed of an upper sediment layer that is known to be a low speed inclusion that gets thinner with range and pinches out at 8-9km. An internal reflector with a relatively constant separation of ~20m from the water sediment interface can be seen.

(a) (b)

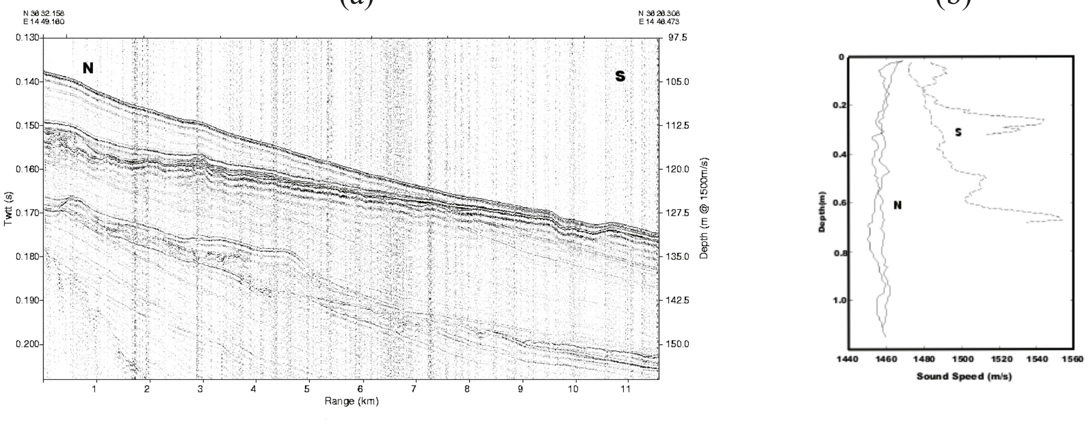

Fig.1: (a) Seismic profile along the Malta Plateau track - (b) Sediment corings taken in the vicinity of the track

Interestingly enough, the design of the experiment was close to the one considered in the simulation study given in [3]: source and HLA depths around 60m; source-receiver horizontal separation of around 320m. In this paper, the authors performed a comparison of inversion results obtained with a BOUNDARY 2003 - BASE’04 like set up (relatively high frequency between 850-1850 Hz and short array ~ 35m) and a MAPEX 2000 like set up (lower frequencies between 250-750Hz and longer array 250 m). This study showed, with simulated data, that the first set up had lower performances to resolve multi-layer structure of the seabed than the second one.

As a consequence, the Malta Plateau track constitutes an excellent test case to assess with real experimental data set those conclusions. Moreover, as a well documented area, it also provides the opportunity to compare results of inversions with different settings of the inversion algorithm. As a matter of interest, a blind inversion point of view has also been considered in order to propose the basis of a blind supervised inversion strategy that could fit the constraints of an operational ASW scenario during which nearly real-time inversions results and assessment of the quality of the inversion results are required.

4.1. Resolving multi-layer seabed structure

Within the context of a blind inversion strategy, it is thought that a pragmatic approach of the inversion problem may consist in looking for the seabed structure by iterative steps until a "sufficient" match is obtained. As a first approach, ignoring the groundtruth that we had along the Malta Plateau track, the seabed model has been constrained to be looked for under 4 different forms: semi-infinite fluid half space with a water depth constrained to be around the true bathymetry, semi-infinite fluid half space with free water depth, single sediment layer over a semi-infinite basement and two sediment layers above a semi-infinite fluid half space. In the following sections, they will be referenced as respectively, SemiInfinite-WD Constrained, SemiInfinite-WD Unconstrained, 1-Layer and 2-Layer models. In the following section, the results have been obtained by down-sampling the available data: only 21 hydrophones over the 84 of the HLA and a frequency sampling of 50Hz between 850-1750 Hz have been taken into account. This configuration will be referenced as the dense array configuration in the following sections. A total of 61 pings all along track (1 ping every minute) have been inverted.

In Fig.2, the lowest values of the cost function after inversion for all pings and the four types of inversions are presented. The Bartlett processor provides a value between 0 and 1, 0 meaning a perfect match between simulation and measurements. Globally, the 1-Layer model gives rise to the best matches. Importantly, for ranges below 6.5 km, the SemiInfinite-WD constrained has much higher level of mismatch than the three others that have all rather close cost function values. Beyond 6.5 km, the match is rather similar with all the inversions.

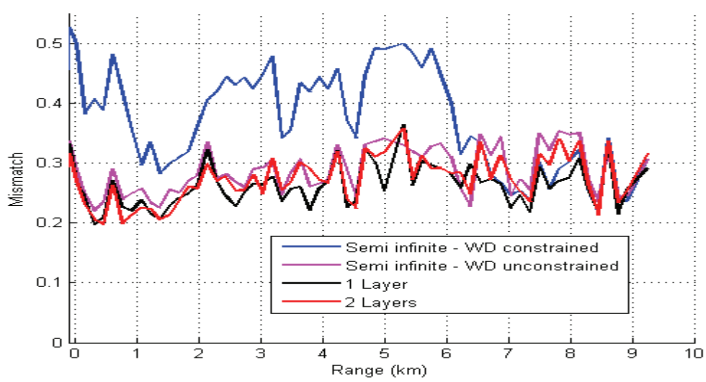

Fig.2: Final best match values after inversion for the 4 inverted models and the 61 pings.

Fig.3 shows a stack of the best ping-to-ping inversions obtained all along track. Noticeably, the two semi-infinite models (a)-(b) characterize the same interface beyond 6.5 km (ie. the first internal reflector). Indeed, beyond 6.5km, for the SemiInfinite-WD constrained model, the inversion algorithm was allowed to look for the water depth in a depth interval that included the true bathymetry and the first internal reflector. As a result of the low compressional speed characteristics of the upper-layer, the upper sediment is nearly acoustically transparent. When leaving free the inversion algorithm to look for the water depth (SemiInfinite-WD unconstrained), this one finds the buried interface that has a highest impedance contrast than the water-seabed interface.

As for the 1-Layer model (c), it can be noticed how remarkably the inversion algorithm manages to follow the seabed interface and the first internal layer. Few pings beyond 6.5km, are found to match the basement interface which tends to prove that the acoustical data convey some information about this one.

Analysing the 2–Layer model, it can be seen that the first internal interface is also pretty well inverted. Some apparent variability can be seen at the end of the track: as the seabed structure is constrained to be composed of 2 sediment layers, a fictive internal layer is found as an artefact of the initial parametrization of the inverse problem. In reality, acoustical properties of both upper layers are close one from the other (see Fig.3), resulting in an actual single layer. As for the basement interface, its inversion is a little bit more variable, explicitly showing a limited but still existing sensitivity of the inversion to that layer.

Finally, it can be noticed that within the scope of a blind inversion scenario, the "fusion" of both SemiInfinite inversions could have led a supervisor to guess the existence of an internal layer. Indeed stacking the ping-to-ping inversions of the SemiInfinite – WD Unconstrained model gives rise to a rather smooth interface with little variability that looks like "natural" .

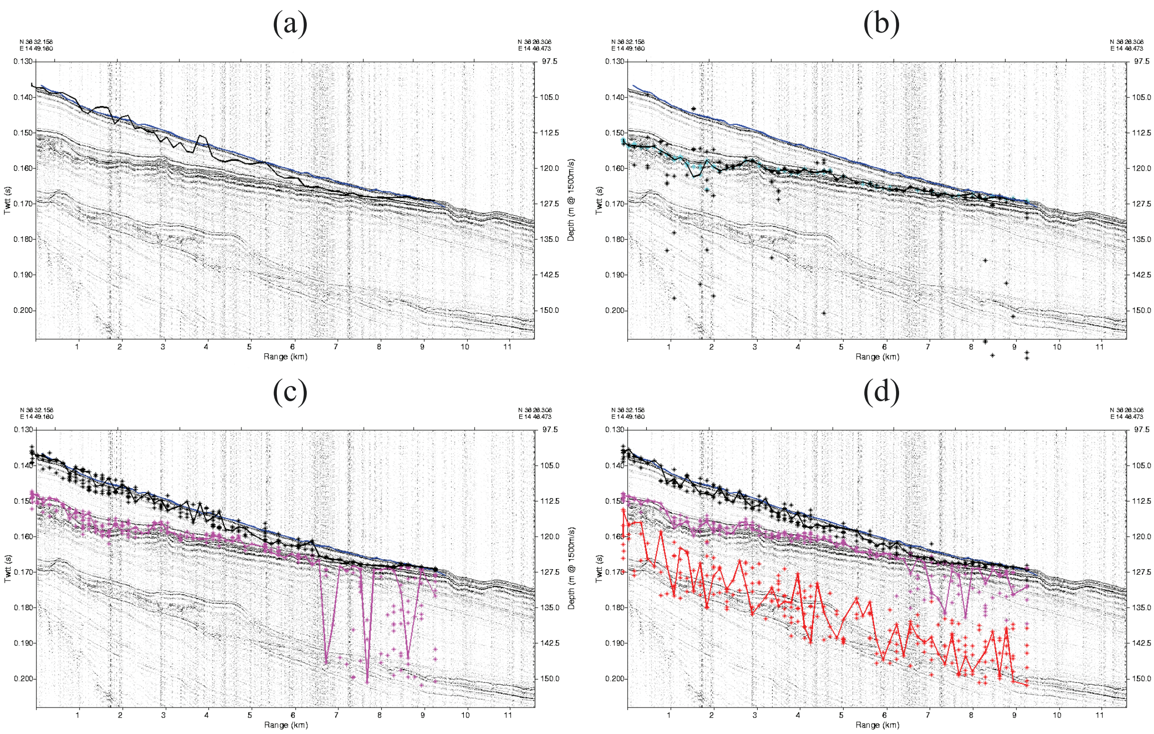

Fig.3: Inverted seabed structure- (a): SemiInfinite- WD constrained - (b): SemiInfinite-WD unconstrained- (c) 1–Layer – (d) 2-Layer

Fig.4 provides the inverted geoacoustic parameters of each sediment layer. Due to the known lack of sensitivity of the inversion to some of the parameters, the seabed structure has been simplified for some of them. For example, a unique density value has been searched for all of the layers for the 1-Layer and the 2-Layer models. The same idea has been applied for the attenuation of the second layer and the basement for the 2-Layer model. The compressionnal speeds obtained for the upper sediment layers and the basement of the 1-Layer and the 2-layer models are in rather good agreement with previous geoacoustic inversion results [1][2] obtained along the same track, or the available ground truthing data. Anyway as shown in [3], the compressional speed of the basement could be overestimated, and should thus be taken as it is, ie. as an effective parameter of the seabed properties that enables afterwards the acoustical model to replicate the acoustical pressure field at short ranges along the HLA.

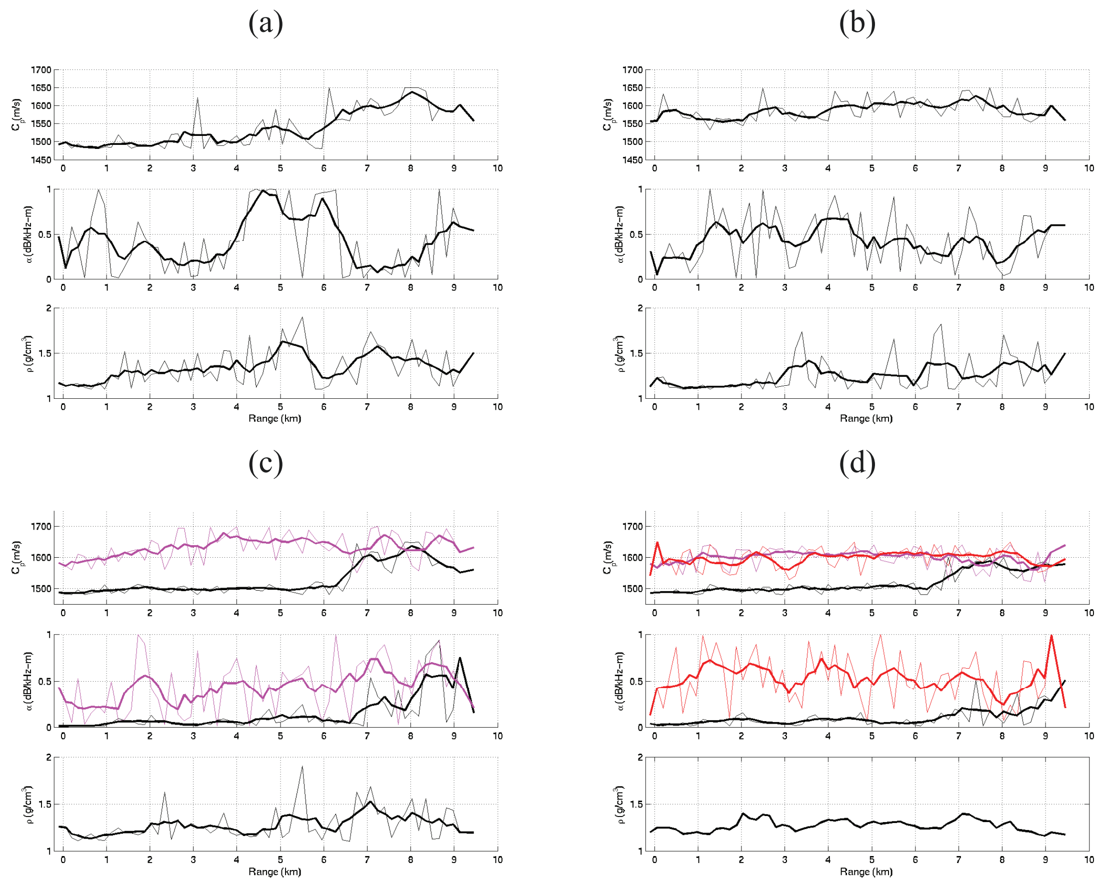

Fig.4: Inverted geoacoustic parameters. The same codes of colours as those of Fig.3 have been used. For a given colour, the geoacoustic parameters are the ones of the sediment layer below the interface of the same colour in Fig.3. Bold curves correspond to mean ping-to-ping filtered results of the inversion. Raw ping-to-ping inversion results are shown by the thin lines. (a): SemiInfinite- WD constrained - (b): SemiInfinite- WD unconstrained - (c) 1–Layer – (d) 2-Layer

4.2. Using a sparse array configuration

A similar analysis has also been performed using a sparse array configuration limited to 5 hydrophones (instead of 21) and a denser frequency sampling (1Hz). Interestingly, one should note that Eq.(1) is equivalent in the frequency domain to the standard matched-filter processor. The relevantness for geoacoustic inversion purposes of model-based matched filter (MBMF) inversion techniques in the time-domain with sparse vertical arrays or horizontal array has been demonstrated. By applying a 1Hz frequency sampling in Eq.(1), the standard MBMF approach and the one used in the present study should thus be rather equivalent since the 1Hz frequency sampling would result in a time gating of 1s in the time domain. This is far sufficient to catch the whole tail of the waveguide's impulse response. Fig. 5 presents the results of the inversion. Once again, below 6.5km it can be noticed a remarkable match between the inverted seabed structure and the seismic profile, as well as an excellent agreement between the geoacoustic parameters inverted that way or those obtained with a dense array configuration (see section 4.1). Beyond 6.5 km, an apparent variability of the seabed internal layer can be observed. A careful analysis of the inverted seabed structure and the inverted parameters shows that, this variability is most of the time due either to the fact that the basement is correctly determined, or to an artefact of the initial parametrization of the inverse problem (ie. for some of the pings, the geoacoustical properties below both inverted interfaces are similar, which means that both sediment layers can be fused in a single one).

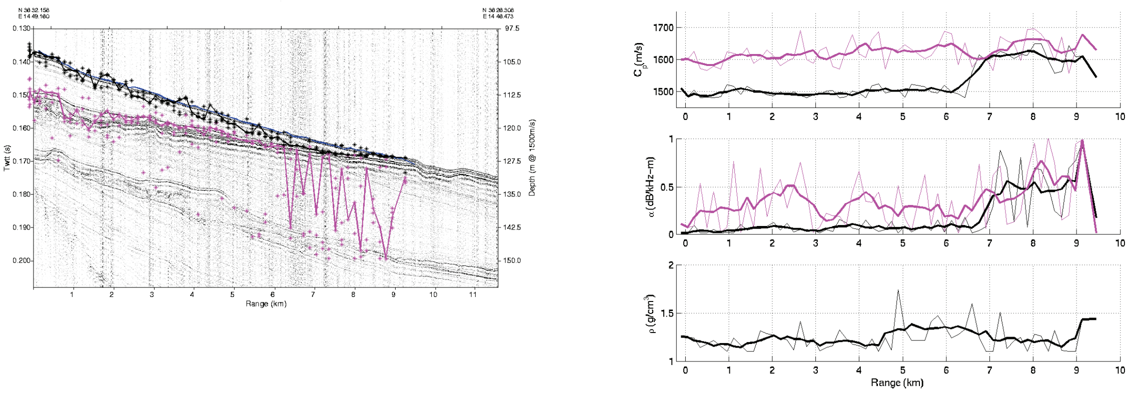

Fig.5: 1-Layer inversion using a sparse horizontal line array configuration.

4.3. Using other Bartlett processor

Coming back to a dense array configuration, two other types of Bartlett processors (Eq. (2) - coherent in range –incoherent in frequency) and (Eq. (3) coherent in both range and frequencies) have also been tested. Except for very few pings and quite surprisingly, only slight differences could be seen in the inversion results (not shown here).

$$\phi = 1 - \frac{1}{N_f}\sum_{j=1}^{Nf}\frac{\left|\sum_{i=1}^{N_r} p_{ij}^{*} q_{ij}\right|^2}{\sum_{i=1}^{Nr}\left|p_{ij}\right|^2\left|q_{ij}\right|^2} \qquad (2)$$

$$\phi = 1 - \frac{\left| \sum_{j=1}^{N_f} \sum_{i=1}^{Nr} p_{ij}^{*} q_{ij} \right|^2}{\sum_{j=1}^{N_f} \sum_{i=1}^{Nr} \left| p_{ij} \right|^2 \left| q_{ij} \right|^2} \tag{3}$$

5. SUMMARY

This study has shown the ability of the TTS concept to robustly and trustworthly assess the local seabed geoacoustical properties of a multi-layer and range dependent environment of the Malta Plateau. Results have shown that consistent results could be obtained by inverting for relatively high frequency (850-1750 Hz) acoustical data acquired along a short array (~35m). Different settings of the inversion algorithm have been tested and have shown similar results. Applied in a blind inversion context and thanks to the rather smooth shape of the found internal interfaces, it appears that, reasonably, a ping-to-ping supervised analysis of the inversion results would have led an advertised operator to successfully guess the seabed structure and its main geoacoustical properties.

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