Real-time geoacoustic inversion
of large band signals

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Abstract - **This paper describes the development of a real time geoacoustic inversion tool devoted to large band signals. The aim of this tool is to automatically infer geoacoustic bottom characteristics from transmission sound field pressure measurements in a deep ocean medium. The first part of the article is devoted to the direct problem. It describes the functionalities of the propagation simulation tool and its automatic connection with measurements parameters. Then the paper deals with an inversion method based on recent works on the subject in the scientific community. Finally real-time architecture and some concrete results obtained with in-situ data in the gulf of Oman are presented.**

I. INTRODUCTION

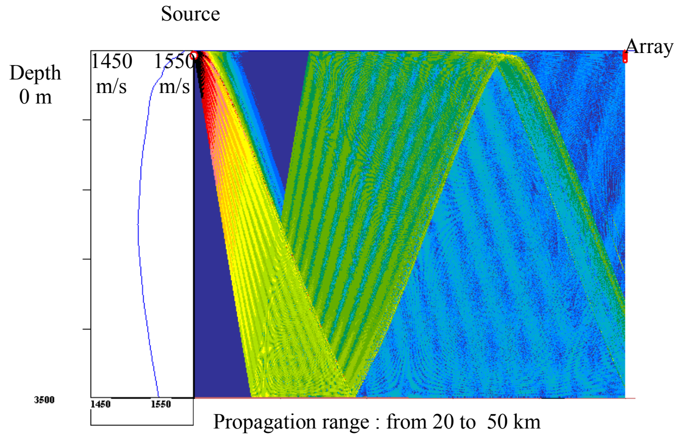
The work presented here follows studies and research conducted by EPSHOM/CMO in the geoacoustic inversion domain during the last ten years [1] [2]. The novelty resides here in both real time methods and the focus on a deep-water configuration. This new research orientation is guided by operational interest in sonar performance assessment. The inverse method developed is able to infer some bottom parameters from a small package of bottom reflected rays whose characteristics are measured.

The three first parts of the article describe a measurement campaign in the gulf of Oman, propagation simulations and the automatic connection between them, allowing identification. Then the paper deals with an inversion method, based on recent works on the subject in the scientific community and more specifically in EPSHOM/CMO [2]. Finally real time architecture and some concrete results obtained with in-situ data in the gulf of Oman are presented.

II. ACOUSTIC MEASUREMENTS

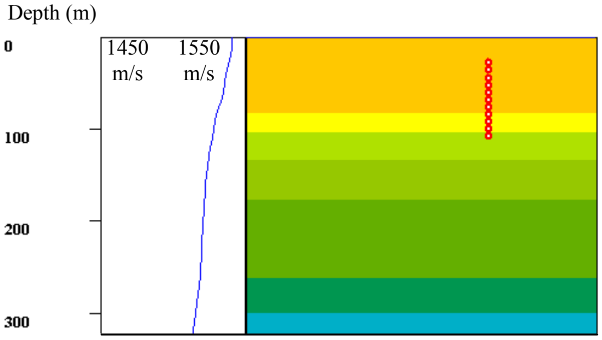
A measurement campaign was conducted in the gulf of Oman in 2002. Fig.1 shows an example of ray tracing in the used experimental configuration, whereas Fig.2 presents source and array locations. A drifting vertical array (surface buoy) is made of 11 hydrophones sampling the first 100 meters. The acoustic source is towed at 100 m. The propagation range is between 20 and 60 km, crossing the convergence area. Four transects have been recorded localized above different sedimentary type bottom areas. The ray trajectories admit grazing angles from 15° at the beginning of the transects, to 5° at the end.

The emitted signal is made up of broadband pulses, typically between [300 Hz, 1 kHz], with a recurrence of one minute. Fig. 3 shows a time evolution of the measured impulse response along the R2 transect. Bottom reflected rays with one or two reflections are clearly visible. The first convergence area is clearly unlit by red color growth.



Propagation range : from 20 to 50 km

Fig. 1. Ray tracing



Propagation range : from 20 to 60 km

Fig. 2. Experimental configuration: source and hydrophone depths

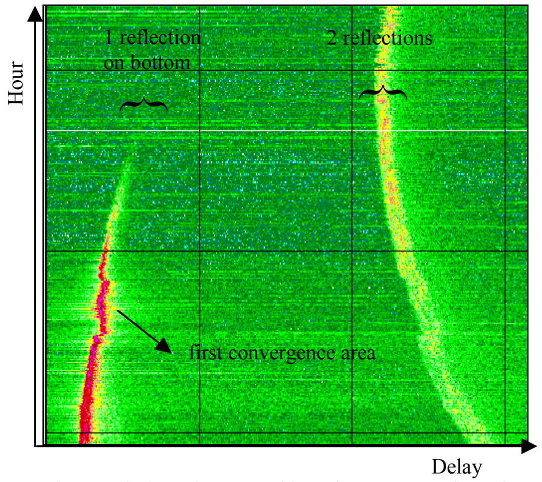


Fig. 3. Time evolution of measured impulse response along the R2 transect).

III. ACOUSTIC SIMULATION PROPAGATION

Fluid sediments and multi-layered bottoms have been taken into account in the acoustic propagation simulator RAYSON [3] [4]. Automatic computation based on impulse responses for different bottom types is operational.

Calculations are done for the 11 hydrophones and for a bottom relative to different kinds: rocks or fluid sediment with porosity. The fluid sediment model is that of Hall and Watson [5] [6]. In this case the propagation loss is given by (in dB):

$$\begin{aligned} P_{dB} &= \left[3.7 + 17.5\left(\overline{P} - 0.27\right)\right] f^{1/3} \left\{ tgh\left[\left(\frac{\pi\theta\,\overline{P}}{180.0.24}\right)^{\frac{1.5}{P}}\right] + \frac{1 - \frac{\overline{P}}{0.27}}{12.5}\left(\frac{\theta}{90}\right)^{2} \right\} \\ &= 10\log_{10}\left[p_f^2\right] \end{aligned} \tag{1}$$

where

- P is the porosity between 0 and 1
- f is the frequency in kHz
- θ is the grazing angle in degrees

Sand and mud are particular cases of fluid sediment for which the porosity is 0.4 and 0.7 respectively.

IV. IDENTIFICATION

Specific software has been developed to examine and compare measurements and simulations of impulse response signals. The aim was to allow automatic superposition of the two signals. This is a necessary step for both multi-sensor fusion and real time approaches.

The software accepts as input time 'Y/M/D h:m:s' and is able to extract experimental and environmental parameters relative to that time, to launch the corresponding simulation computations and to show the following outputs, for each of the 11 hydrophones:

- Measured impulse response
- Simulated impulse response

The following figure shows an example of simulated and measured impulse responses for the four first hydrophones.

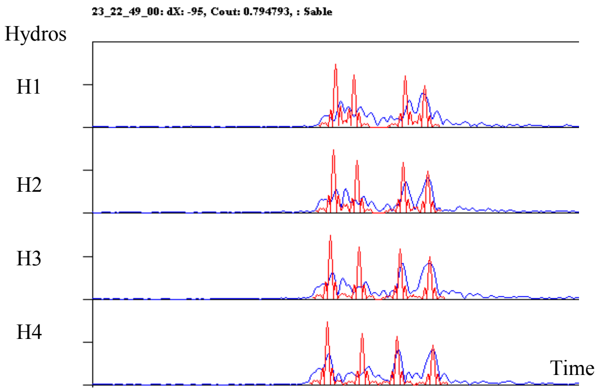


Fig. 4. Simulated and measured impulse responses for the 4 first hydrophones at time '2002/03/23 22:49:00'

At this stage all the data necessary to proceed with an inversion have been automatically generated and gathered for each considered instant.

V. COST FUNCTION

Our work first focused on the way to infer bottom characteristics in real time from acoustic transmission measurements. The aim was to show feasibility of the automatic real-time inversion chain. For that purpose we have worked with a simple cost function and inversion method. A second stage will be then, once feasibility has been proven, to improve both.

The cost function used in the inversion method is defined by the normed quantity:

$$\frac{\left|Sfc[FA(t), RI(t)]\right|}{Sfc(FA(t))} \tag{2}$$

where

- *FA(t)* is the measured impulse response
- *RI(t)* is the simulated impulse response
- *Sfc* is the area between the two curves

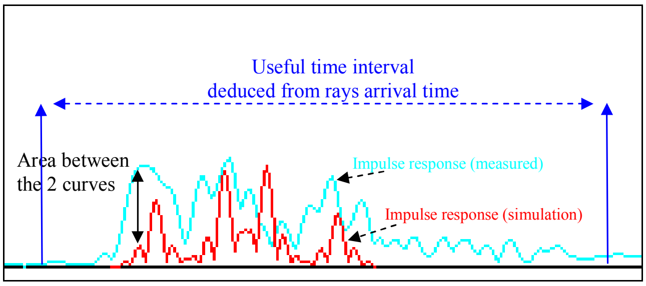


Fig. 5. Cost function

For the eleven receivers the normed cost function then becomes:

$$\frac{\sum_{n=1}^{11}\left| Sfc[FA_n(t), RI_n(t)] \right|}{\sum_{n=1}^{11}\left|Sfc(FA(t))\right|} \tag{3}$$

VI. INVERSION METHOD

A. *Introduction.*

The inversion is realized with a matched Impulse Response method, based on exhaustive exploration for the parameter couple (D, T) , where :

- D is propagation range
- T is bottom-type among rocks or fluid sediment as defined by the porosity P

The two parameters are inverted simultaneously. Two stages are necessary:

- The first stage consists of propagation range inversion. This phase cannot be done by a complex inversion method like simplex because evolution of the impulse response versus D is not a monotone function. Output is $\underline{D}$, which is an approximate value of D.
- The second stage is devoted to bottom-type inversion. During this phase, the value of $\underline{D}$ is refined to D, and the bottom type T is determined.

B. *Stage 1: Propagation range inversion and D estimation*

A first step is necessary to restrict the search domain: under the assumption that the ray arrival time has a weak dependence on receiver depth, simple rays trajectory characteristics are used first to extract the smallest useful arrival time called $t_{min}(D)$. This is done for N samples of propagation range and typically D exploration is +/- 300 m with a 5 m step.

Then the algorithm of this stage is the following:

- A useful time interval $t_{min}(D)$ is determined for several values of D, and the procedure keeps only the data included in this interval.
- The time T_{min}, relative to the first time arrival, is measured on real signals
- Then an algorithm based on matched impulse response with the cost function (cf. preceeding paragraph), looks for the $\underline{D}$ value, which satisfies:

$$t_{min}(\underline{D}) = T_{min} \qquad (4)$$

This assumption allows us to work with the simple ray nearest to the eigenray, instead of working on the eigenray itself. This implies an important saving in computation time, because simple rays are faster to determine. This method enables a consequent reduction of the search time and a ratio between 5 and 16 is obtained by comparison with a classical method based on eigenrays. That means that the time required to inverse a run (an impulse) becomes 1 minute instead of 10 minutes.

C. *Stage 2 : Bottom-type inversion*

In this stage D is refined and T is determined. The algorithm proceeds first by computing eigenray bundles for 10 range propagation intervals: this is typically done for a D search of +/- 25 m with a 5 m step.

Then the algorithm of this stage is the following:

- For each simulated bottom type, 11 impulse responses are computed, as well as the global cost function.
- The cost function is then minimized for all the 11 hydrophones over the ensemble of:
    - 10 propagation ranges
    - 10 bottom types

The result of the minimization is the solution pair (T, D) chosen among 10 distances and 10 bottom types. The next paragraph analyses the results of this method on real data inversion.

It is interesting to note that if the bottom-type number is less than 100, matched IR works well and is just limited by the eigenray computation time. On the other hand, for a number of bottom types which exceed 100, it becomes more attractive to improve the inversion method by the use of a more sophisticated method, like the simplex method for example. This remark validates the interest of implementing this algorithmic architecture for small quantities of bottom types with a basic inversion method. Since the algorithms are in place and respect real-time constraints, a future stage will consist of improving the inversion routines and increasing the search domains.

VII. RESULTS ANALYSIS

A. *In situ environmental knowledge*

This paragraph shows first results obtained with real data. It is interesting to note that the inversion method has been developed with a real acoustic data set, but without precise knowledge of the sedimentary structure of the area. The structure presented below was compared only at the end of the inversion method development. Fig. 6. presents the sedimentary structure of the area, superimposed with the source and receivers tracks during the R2 transect.

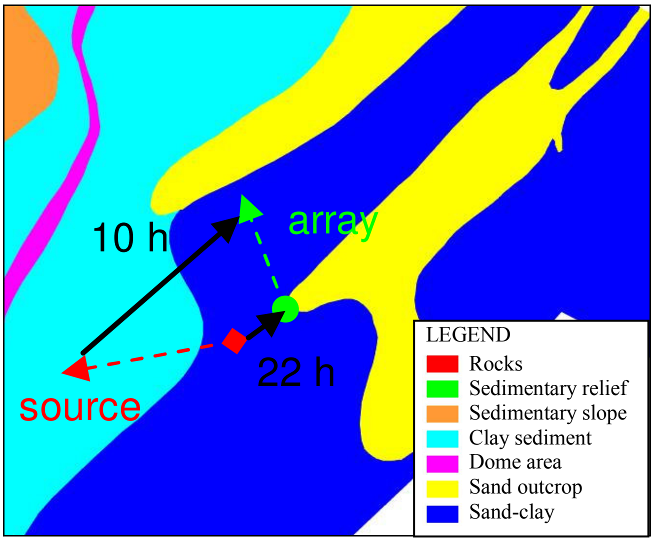


Fig. 6. Sedimentary map of the experimental area. R2 transect lasted from 23/03/02 22h to 24/03/02 10h. Source trajectory during R2 transect is represented in red. Array track is in blue.

At the beginning of the R2 transect, acoustic reflection occurs on a sand-clay bottom, and at the end on a clay bottom. This has to be compared to outputs of the inversion method. During the campaign, five bottom samples were taken in the area. The structure of these samples was used to determine the reflection coefficients which are shown at 900 Hz on Fig.7.

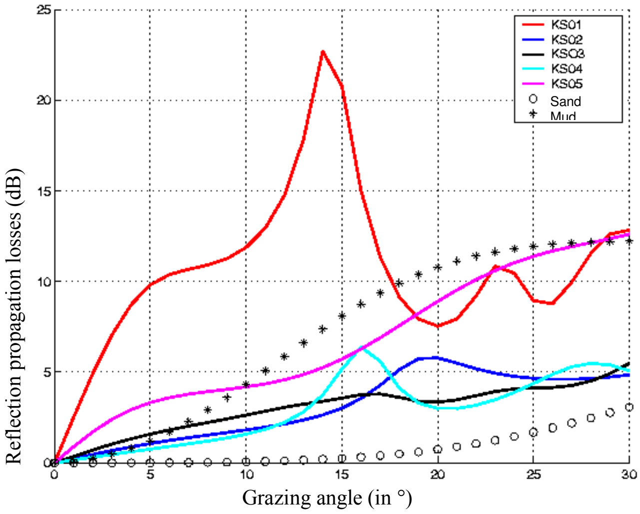


Fig. 7. Reflection coefficients at 900 Hz relative to the 5 structures sampled, and to typical sand (porosity = 0.4) and mud (P = 0.7)

In the experimental configuration, the interval of grazing angles used is approximately [5°, 15°]. Comparison of the structure of the reflection coefficient with those of typical sand and mud, leads us to conclude that:

- At the beginning of the R2 transect, the bottom (made of sediment like sample KS02) acoustically behaves like a sediment that is a compromise between sand and mud.
- At the end of the R2 transect (grazing angles are below 10°), the bottom looks like mud, but a little more absorbing.

A. *Comparison with inversion method results*

Fig 8 shows values of the porosity obtained with the inversion method. Notice that a porosity "equal to zero" is currently allocated when the inversion method does not give a solution. This happens a few times when the first arrival time is not steady and does not prevent the method from continuing to run after crossing the unsteady convergence area.

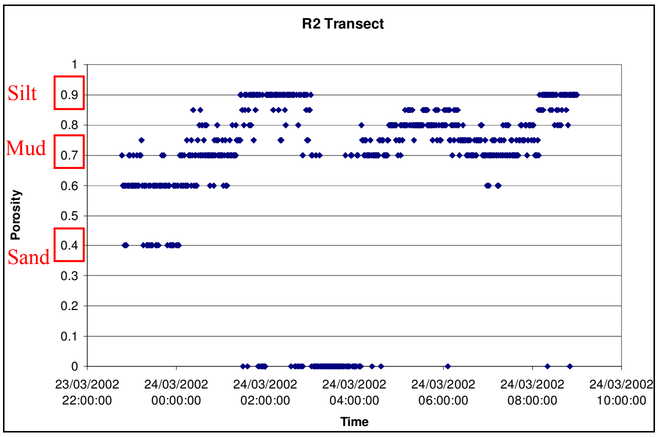


Fig. 8. Values of porosity obtained along the R2 transect with the inversion method. Typical values for sand, mud and silt are given in red.

At the beginning of the R2 transect, porosity values are found between 0.4 and 0.7, admitting a mean value of 0.6 that actually corresponds to a compromise sediment between sand and mud. During the two-third part of the R2 transect, the inverse method finds a mean porosity of 0.8 corresponding to a sediment between typical silt and mud. We conclude that the results look relevant with in-situ sedimentary knowledge.

B. *Performance of computation ties*

Computations have been made on a PC station with the following characteristics: Athlon 64 3500+ - 2 Go RAM - 210 Go.

The order of magnitude for computation time is around 2 min per ping divided as follows:

- Inversion stage 1 : around 1 min. per ping,
- Inversion stage 2 : around 1 min. per ping, that means 2 pings are processed per minute at the beginning of the transect, when 2 min are needed for one ping at the end of the transect.

Before introduction of the optimization with simple rays instead of eigenrays in stage 1, the time needed to process one ping on eleven hydrophones was 40 min.

These time values respect time consuming constraints required in Rapid Environment Assessment (REA) applications.

VIII. CONCLUSIONS - PERSPECTIVES

This work constitutes a first step in the development of a real time geoacoustic inversion devoted to large band signals and deep water environments. It shows that the data contain information which looks relevant, and proves the opportunity to infer in real-time, from a small group of bottom reflected rays, some bottom parameters. The results display well the notion of an equivalent medium, characterized here for a grazing angle interval [5°, 15°].

Perspectives are now to continue working with more complex inversion methods and bottom parameterizations. The aim is to interpret more finely the bottom characteristics, as experimental area samples have shown a more tangled stratified structure.

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