Translated Article

Operational Feasibility of the Geoacoustic Inversion of Equivalent Media: Principle and Application to the INTIMATE96 Data

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The geoacoustic parameters of the bottom have a major influence on sonar performance, especially at very low frequencies. To optimise sonar predictions, it is necessary to rely on a geoacoustic model of the bottom which provides a good estimate of the propagation and reverberation in the real medium. Such a model must also fit operational constraints at the calculation times. There are two complementary approaches.

The first approach attempts to estimate the geoacoustic parameters from direct measurements. This approach, which is often called 'ground truthing', is mainly based upon the data from coring and sediment sampling. These methods are usually associated with indirect acoustic measurements (sub-bottom profiler, multi-beam echo-sounder, sediment classifier, side-scan sonar). The measurement of the ground truth is well-suited to the constitution of environmental data bases for the geophysical characterisation of the bottom. However, for two main reasons, this approach is long and impractical for operations of Rapid Environmental Evaluation (REA). First, the coring and sampling results cannot be extensively analysed on site, and the correlation with the indirect methods needs human expertise. Second, certain parameters are sometimes almost non-measurable (sediments attenuation and substratum properties). Moreover, the direct methods do not take into account the operational fidelity (mostly in terms of sensors) and the resulting geoacoustic model is not always suited to efficient sonar use.

The second approach, dealt with in this report, consists of the evaluation of the geoacoustic parameters by a sonar-like measurement. The idea is to use the impulse response of the waveguide to estimate the geoacoustic parameters of the medium.

This approach is generally called 'geoacoustic inversion' (see for example Chapman et al, 1998). Resulting models of the bottom can be good approximations of the real medium, particularly at very low frequencies. These models can also be built as 'equivalent bottoms', meaning that they have the same acoustic response as the real medium for a defined application (Demoulin and Garlan, 1997). Obviously, such an approach does not give the ground truth, and is not completely appropriate for the characterisation of the bottom. However, it has the major advantage of providing a simple model, for which propagation and reflection characteristics are like the real medium. The equivalent medium is then the medium as seen by the sonar. In comparison with the ground truth, this approach can be called the 'sonar truth'.

Most of the inversion techniques for the estimate of the acoustic properties of the sub-bottom are based on the spatial and temporal analysis of the acoustic pressure field (Dosso et al, 1993, Gerstoft, 1995, Rajan et al, 1987, Fallat and Dosso, 1999). These methods generally require several runs of computationally heavy models, which makes them expensive and impractical for operational applications. Also, using monochromatic or multitone signals there is a need to deploy vertical or horizontal arrays. The processing methods of such signals are often unstable due the fluctuations of sensors positions and environmental parameters (water depth, seastate, etc...). A new trend in geoacoustic inversion is to use wide-band signal processing on a restricted number of hydrophones (Hermand et al, 1998). The temporal spreading of the impulse response of the wave guide and the amplitude of the bottom-reflected rays can lead to precise and robust estimates of bottom properties (Hermand, 1999). However, the use of the latter approach remains expensive and implies a relatively complex forward model.

This paper proposes an original approach, combining the equivalent medium concept for the propagation and the broadband inversion concept. This approach is based on analytical developments of the reflection coefficient to find the geoacoustic properties of the equivalent medium. This method avoids heavy and costly calculations, and can be interpreted like a 'sonar truth' approach, as the resulting model of the bottom is suited for the sonar which has been used. On the other hand, the model cannot be generalised: it is only valid for a specific frequency band and a restricted beam of angles (typically low grazing angles). The inversion takes two steps and only requires an acoustic simulation from a standard model. This approach has been successfully tested against the data of the INTIMATE96 experiment (Stephan et al, 1998) on wide-band signals between 300Hz and 800Hz. This article is organised as follows: The second part discusses the measurement scheme taken during the INTIMATE96 campaign, and gives a brief analysis of the acoustic data. The third part gives a detailed presentation of the forward problem. The analytical formula is described. The fourth part presents the inverse problem. The application of the method to the real data is shown. Conclusions and perspectives are given at the end.

2. The INTIMATE96 Campaign

2.1. Instrumental Strategy

The main objective of the INTIMATE project was the observation of the internal tide by means of acoustic tomography (Demoulin et al, 1997, Stéphan et al, 1998). However, the data analysis happened to be more interesting than expected, not only allowing an estimate of the main characteristics of the internal tide (Stéphan et al, 2000), but also allowing tracking of the acoustic source (Porter et al, 1998, Jesus et al 1998), and bottom geoacoustic parameter assessment (Demoulin et al, 2000), which is discussed in this paper. The first sea trial, called INTIMATE96, was carried out in June 1996 on the Portuguese continental shelf, north of the Nazaré canyon (Figure 1). This experiment was led by the SHOM (Service Hydrographique et Oceanographique de la Marine) and by the Instituto Hidrografico of Portugal (IHP), in collaboration with the University of Algarve. A broadband acoustic source was towed by the oceanographic vessel *d'Entrecasteaux*, and the receiver was a vertical four-hydrophone array. Acoustic data was collected during five days, including station phases and towing phases. Received signals were processed in real time on board the Portuguese vessel *NRP Andromeda*. Intensive environmental measurements were also performed (XBT, CTD, bottom-mounted ADCP, thermistor chains, bathymetry). Three phases have been distinguished:

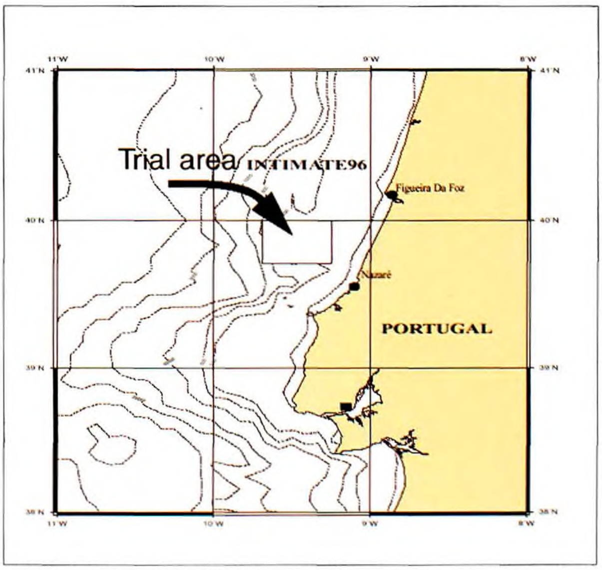

Figure 1: Site of the INTIMATE96 experiment

- an acoustic station 5.6km north of the vertical array
- a phase of towing, with the source being towed at different depths and ranges, and along different directions
- an acoustic station 6.8km west of the vertical array

A seismic survey (sparker system) covered the area, prior to the campaign, and core logs were collected for the sub-bottom characterisation. An environmental description along the north-south leg, corresponding to the first acoustic station is given in Figure 2.

2.2. Data Interpretation

The transmitted signals were chirps between 300Hz and 800Hz. The chirps lasted 2 seconds and were repeated every 8 seconds (the time of transmission was controlled by GPS). The received acoustic signal was cross-correlated with the transmitted signal (matched filtering). All the reception sequences were aligned to the first energy arrival, in order to be independent of the fluctuations of the sensors location. A typical reception sequence, for a source at 90m and a receiver at 115m, is presented in Figure 3. This sequence is divided in two parts. The first part is composed of direct arrivals, refracted by the thermocline and/or with a small number of surface and bottom reflections. The second part is composed of bottom and surface reflected rays. This part is remarkably stable, meaning that it does not fluctuate a lot with time. Only the arrival time shifts, following the effects of the internal tide, which induces a modification of the mean sound speed over the water column, and the effects of the external tide, which produces a change in the water level.

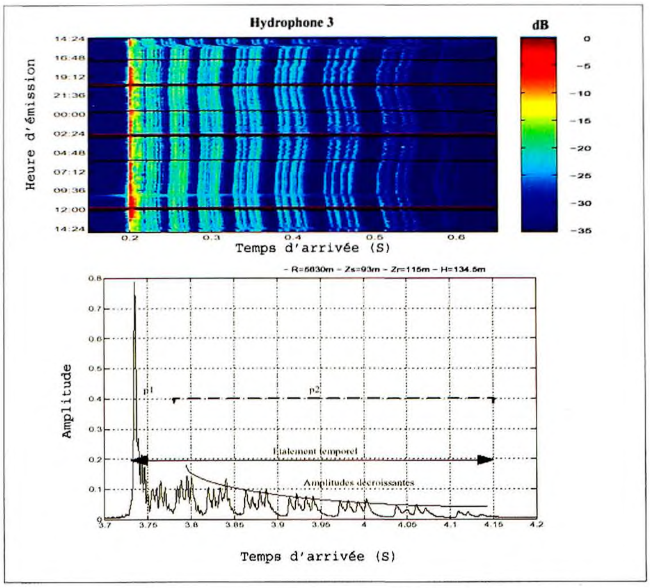

Figure 3: Top: Acoustic data collected on hydrophone 3 (115m) during the 24-hour station. All the received sequences are aligned on the first arrival. The last part of the signal is composed of the multipath returns from the bottom and surface.
Bottom: Typical sequence received (summation of data) over 30 minutes. The bottom effects induce a temporal extension of the sequence and a decrease in the amplitude of the reflected signals. The stable part of the signal is represented by the part p2, the fluctuating part due to sound speed profile fluctuations, is represented by the part p1

The stability of the bottom-reflected signals, suggests that the treatments performed on this part can be generalised for other shallow-water configurations. The bottom has two major influences on the impulse response of the medium. First, considering a semi-infinite fluid medium, the last visible rays are reflected with the angles nearest to the critical angle, which is the maximum angle above which the signals cannot be reflected

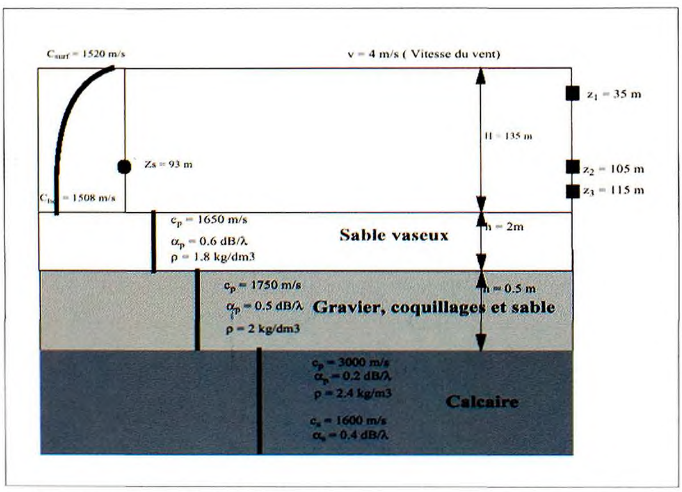

Figure 2: Experimental device and environmental parameters of the acoustic station in a range independant medium

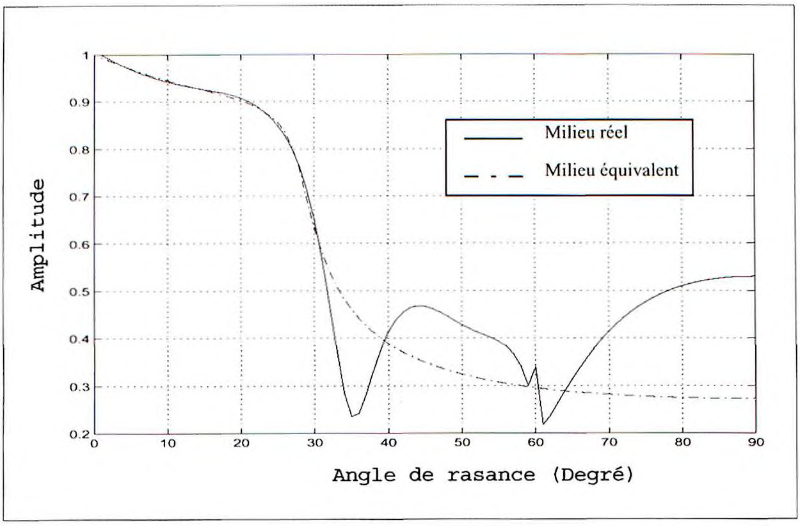

Figure 4: General shape of the reflection coefficient at the main resonance of the source (650Hz) in the INTIMATE96 environment (solid line). The reflection coefficient of the equivalent medium (semi-infinite fluid bottom) is shown as a dashed line. The correlation is almost perfect for the subcritical angles (angles below 30 degrees)

but are transmitted into the bottom. Consequently, the temporal spreading of the impulse response of the medium can be at first approximation interpreted as an indirect measure of the critical angle, this angle depending on the compressional speed of the sea floor. The amplitude of the reflected signals from the bottom decreases with the number of reflections, and equivalently with the times of arrival. Then, the amplitude of each reflected ray, as well as the decreasing of these amplitudes, from one ray to the next, can be seen as an indirect measure of the subcritical part of the reflection coefficient. It is then an indirect measure of both the compressional speed and the compression attenuation coefficient. These two ideas form the basis of this work: the measure of the temporal spreading of the signal and of the decreasing of the reflected arrival amplitudes, lead to an estimate of the compressional speed and of the compression attenuation coefficient for the equivalent sediment, defined by a semi-infinite fluid layer.

3. The Forward Geoacoustic Problem

3.1. Interpretation of the Reflection Coefficient. Notion of Equivalent Medium

Equivalent geoacoustics models have been proposed and studied for different reasons such as the modelling using a parabolic equation (Bucker, 1983) or for the study on shear-wave effects (Li and Hudgson 1998). We take up here this concept in an effort to estimate the propagation losses.
The three layers of the geoacoustic model of the bottom encountered during the INTIMATE96 experiment are described in Figure 2. Such a description is not very appropriate to a rapid estimation of the environmental parameters because of the number of parameters to assess and because of the difficulty in performing an *in-situ* measurement, either by a direct or an indirect mean. It is interesting to note that for most of the sonar applications, the performance predictions rely principally on the precision of the estimation of the transmission losses for the low angles (as for the high angles, the energy is rapidly attenuated). In that way, the Rayleigh $R(\theta)$ reflection coefficient is a very effective way of describing the bottom by its acoustic impedance. This coefficient, a function of the grazing angle, comprises two parts separated by the critical angle. The energy of the rays reaching the bottom with an angle greater than the critical angle is transmitted in the bottom. On the contrary, the rays reaching the bottom with an angle smaller than the critical angle, are reflected and continue to propagate within the water column, with an energy attenuated proportionally to the value of the reflection coefficient, for the angle considered. For a given frequency, even in a complex bottom (which can more particularly present resonance effects, surface waves,...), the typical shape of the reflection coefficient at lower angles than the critical angle (the subcritical angles) can often be modelled by a semi-infinite fluid medium, which is the simplest geoacoustic model. This medium is like an equivalent medium as it has the same transmission properties as the real bottom. However, it must be kept in mind that the reflection coefficient depends on

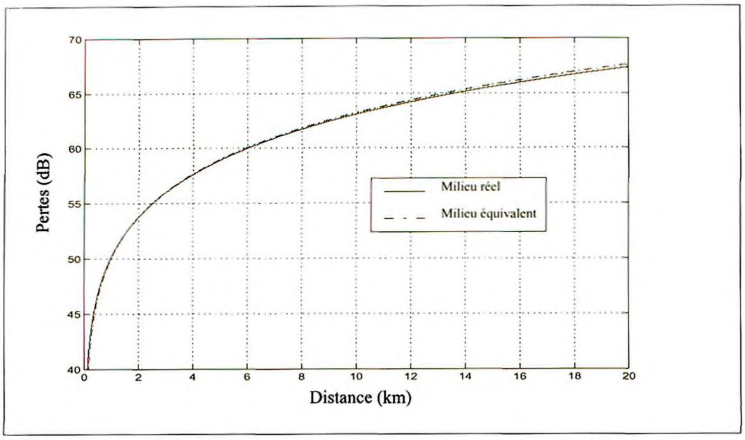

Figure 5: Incoherent propagation losses in the case of the equivalent medium calculated at 650Hz (dashed line) and in the real medium (solid line). The difference is lower than 1dB at 20 kilometres

the frequency. The equivalent medium is only valid over a particular frequency range.
The general shape of the reflection coefficient for the environment of the INTIMATE96 experiment is given in Figure 4. In order to illustrate this idea, the Rayleigh coefficients are compared together in the real environment and in the equivalent medium. The agreement is excellent within the first 30 degrees. The parameters of the equivalent medium are as follows: ρ_b = 1.54Kg/cm^3, C_b = 1711m/s and α_b = 0.87dB/λ. These parameters have been obtained by minimisation of the variations between the reflection coefficients within the first 30 degrees. As will be explained later, these values are very close to the ones resulting from the inversion of the real data, except for the density which does not have influence, The discriminating parameters are the speed and the attenuation of compression. In order to show the operational interest of the equivalent medium approach, Figure 5 shows a comparison of the propagation losses over 20 kilometres within the real medium and within the equivalent medium. The calculation is done at a centre frequency of 650Hz of the high resonance of the transducer used, which was a Janus-Helmotz source. Calculations have been done through the normal mode code KRAKENC (Porter, 1991). The difference in the propagation losses is very small, lower than 1dB at 20km. The representation by equivalent medium seems then perfectly appropriate for the evaluation of the propagation losses in the instrumental context of INTIMATE96.

3.2. Correlation with the Impulse Response

As represented in Figure 6, there is a correlation between the shape of the impulse response of the medium and the shape of the reflection coefficient. First, the duration of the impulse response is a function of the critical angle. Then, the decreasing of the amplitudes is in correlation with the decreasing of the reflection coefficient modulus *R* for the subcritical angles. More precisely, the amplitude of a given beam, being reflected n times of the bottom, is a function of the modulus of *R* raised to the power *n*. Of course, this correlation only concerns the effects of the bottom and the noise coming from the surface reflections can interfere. The analysis of the amplitudes of several beams (with different incident angles) would enable one to retrace the general shape of the

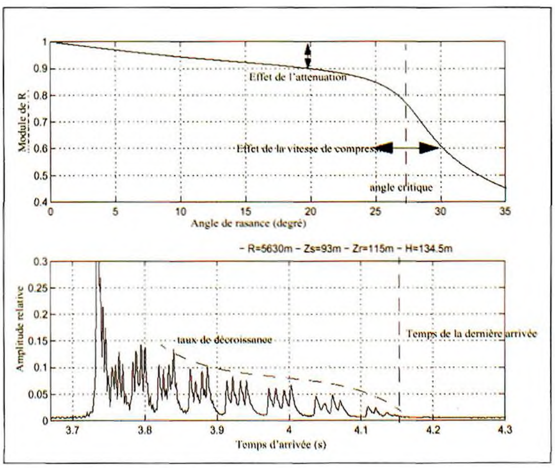

Figure 6: Correlation between the shape of the reflection coefficient and the shape of the impulse response of the medium. The correspondence between the critical angle and the last arrival can be noted. Also, the decrease of the amplitudes of the reflected beams corresponds to the decrease of the reflection coefficient for the ante-critical angles

reflection coefficient. However, this approach implies the identification of all the beams, and the digitally build up of the coefficient at the subcritical angles. Another approach is possible with the use of only one ray, provided that the analytical development of the reflection coefficient is known. In both cases, it seems that if it is possible to measure experimentally the sequence duration and the amplitudes of the reflected beams (possibly filtered of the surface effects), the velocity and the attenuation of the compression wave will be determined by a relatively simple inverse approach. As stated previously, this approach will only be valid for a specific range of frequencies, but the use of wide-band signals should allow the use of equivalent mediums over a relatively wide spectrum of frequencies.

3.3. Analytical Formulation of the Direct Problem

The object of this part is to explain the relationship between the reflection coefficient and the parameters of the impulse response. The first step is to write the Rayleigh coefficient for a fluid-fluid interface. This coefficient is:

$$R(\theta) = \frac{Z_b - Z_w}{Z_b + Z_w}, \qquad (1)$$

where $Z_i = \rho_i . C_i \sin\theta$, b and w corresponding to the bottom and the water.

It is recalled that c_b, complex formulation of the velocity in the bottom, is a function of the compression velocity C_b in m/s and of the attenuation α b in dB/λ as follows:

$$c_b = \frac{C_b}{1 + \dfrac{i \cdot \alpha_b}{2 \cdot \pi \cdot 8,686}} \qquad (2)$$

The bottom density is not a very influential parameter for the signal propagation, as it is mostly affecting the value of the reflection coefficient for the higher grazing angles In this study, we will use the Hamilton relation (1986), which is a relation between the density and the velocity valid for continental shelf sediments:

$$C_b = 2330,4 - (1257 . \rho_b) + 487,7 . \rho_b^2 \qquad (3)$$

The second step consists of the characterisation of the impulse response by two parameters: the time of propagation of the last arrival, noted T_{la}, and the amplitude of a given *i* ray, noted y(θi). In fact, if the emitted levels of the source or hydrophones sensitivities are not known, it is not possible to estimate the absolute levels. The measured amplitude is then proportional to the real amplitude:

$$y^{obs}(\theta_i) = K. y(\theta_i) \qquad (4)$$

where K is an unknown constant. In practise, it is thus preferred to use the ratios between two rays *i* and *j*:

$$R_{sp}^{i,j} = \frac{y^{obs}(\theta_i)}{y^{obs}(\theta_j)}. \qquad (5)$$

The calculation of T_{la} and $R_{sp}^{i,j}$ will be explained later on.

The third step is the search of the analytical correlation between T_{la} and the parameters to estimate C_b and α_b. At first, T_{la} and C_b can be directly linked under two hypotheses:

- The last visible arrival is the one at the critical angle. This implies that the signal/noise ratio is sufficient enough to be able to correctly identify the last arrival, that the critical angle is discriminating enough to generate a sharp disappearing of the rays and at last that the number of arrivals composing the signal is sufficient enough to cover a wide angular area around the critical angle
- The critical angle is high enough so that the travel traces of the reflected rays can be considered as linear

Under this second hypothesis, it can be written:

$$\theta_c = a\cos\left(\frac{C_{moy}}{C_b}\right) = a\cos\left(\frac{D}{D_{la}}\right), \qquad (6)$$

where C_{moy} is the mean velocity in the water column, D is the horizontal distance between the source and the receiver, and D_{la} the travel length of the ray at the critical angle. Noting that:

$$D_{la} = T_{la} . C_{moy} \qquad (7)$$

a simple expression coupling the compression velocity to the arrival time of the last ray:

$$C_b = \frac{T_{la} \times C_{moy}^2}{D} \qquad (8)$$

Otherwise, the amplitude of a reflected ray can be written as a function of the reflection coefficient:

$$y(\theta_i) = \frac{\sqrt{\cos(\theta_i)}}{Di} \cdot e^{-\alpha D_i} \cdot |R_s|^{p(\theta_i)}(\theta_i) \cdot |R_b|^{q(\theta_i)}(\theta_i) \quad (9)$$

The first term is the geometrical dispersion in the hypothesis of a linear trajectory. The second term expresses the volume attenuation where α, in dB/km/Hz, is the Thorp coefficient (for the Atlantic) and D_i the length of the ray trajectory. The terms R_s and R_b respectively correspond to the modules of the reflection coefficients at the surface and at the bottom.
At last, p and q are respectively the number of surface and bottom reflections.
Combining the impulse response and the theoretical ray tracing allows an easy identification of the rays. For a given ray, we then have the following parameters: θ_i, p, q, D_i. The R_s term is estimated from the the seastate, from standard expressions (ie Chapman-Harris). We would then get:

$$R_{sp}^{i,j} = \frac{(|R_{b,j}|^2)^{q_j}}{(|R_{b,i}|^2)^{q_i}} \cdot K \ , \quad (10)$$

where K is a constant independent from the bottom reflection coefficients. It is necessary to have an analytical relation between the reflection coefficient and the value of the attenuation coefficient. This can be done by an asymptotic development of the reflection coefficient. A limited development near 0 is given by (Smith, 1983):

$$|R_b(\theta)| \approx 1 - b\sin(\theta) \quad (11)$$

where b is a function of the density, of the velocity and of the compression attenuation. In our case, this formula is not appropriate, as we are interested in all the angles up to the critical angle. It is then necessary to do an asymptotic development for all the subcritical angles. Following Demoulin (Demoulin et al. 2000), this formula is written as:

$$|R_b|^2 \approx \frac{1 - v \cdot \alpha_b}{1 + v \cdot \alpha_b}, \ \text{with} \quad (12)$$

$$v = \frac{\rho_b^*}{\pi \cdot 8,686 \cdot (A-1) \cdot (1 + \rho_b^{*2})}, \text{with } A = \left(\cos(\theta_w) \cdot \frac{C_b}{C_w}\right)^2 \quad (13)$$

$$\text{and } \rho_b^* = \rho_b \cdot \frac{\cos(\theta_w) \cdot C_b / C_w}{\sqrt{A-1}}$$

Except for too absorbing media, which will be discussed later in this report, this asymptotic expression gives excellent approximations of the reflection coefficient for the subcritical angles. It is shown in Demoulin (Demoulin et al., 2000) that:

$$R_{sp} \approx Cte \cdot \frac{1 + w \cdot \alpha_b}{1 - w \cdot \alpha_b}, \text{with } w = q_1 \cdot v_1 - q_2 \cdot v_2 \quad (14)$$

By using eq (8) and Eq (14), the direct problem for the inversion of equivalent medium can be expressed as follows:

$$T_{1a} = \frac{D \times C_b}{C_{moy}^2} \quad (15)$$

$$R_{sp} = Cte \cdot \frac{1 + w \cdot \alpha_b}{1 - w \cdot \alpha_b}$$

4. Geoacoustic Inversion

4.1. Analytical Formulation of the Inverse Problem

Under relatively simple constraints, it has been shown that it is possible to analytically express the forward problem. This leads to the formulation of the inverse problem as:

$$C_b = F^{-1}(T_{1a})$$
$$\alpha_b = G^{-1}(R_{sp}) \quad (16)$$

The first equation of this system allows an estimate of the compression velocity and of the density. The second equation leads to the compression attenuation. It is easily deducted that:

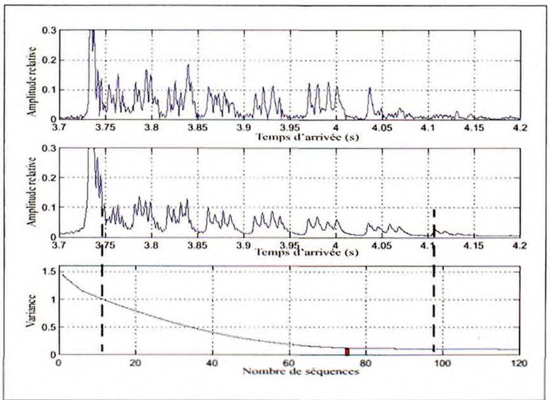

Figure 7: Effect of the incoherent summation on the variance of the received energy. Top: estimated impulse response over a sequence. Centre: estimated impulse response over 75 consecutive sequences (10 minutes). Bottom: variance evolution of the energy in function of the number of summed sequences

$$\alpha_b = \frac{R_{sp} - Ctc}{w \cdot (R_{sp} + Ctc)} \qquad (17)$$

Again it is important to note here that we are looking for an equivalent medium. This simplifies the inversion as, even if the problem is not correctly written because of the multiple solutions, any solution can be retained.

4.2. Inversion of the INTIMATE96 Data

1) Data selection

The data set of the INTIMATE96 experiment is divided into three phases. The first phase contains the data collected during a station of 25 hours, on a range independent environment (flat and constant bottom, north-south direction of the internal tide phase line). A data set of 30 minutes has been extracted. The impulse response to be inverted is the mean impulse response resulting from the sum, after timing and lining up of 75 elementary sequences (mean over 10 minutes). Averaging the sequences enables to get rid of the high frequency fluctuations. This 10 minutes averaging choice is based on the calculated variance of the received energy over all the arrivals reflected at the bottom. In fact, there are a minimum number of sequences to consider in order to minimise this variance (Figure 7).

The trace of the real beams under mean velocity conditions during the campaign allows a very good identification of the rays reflected by the bottom (Figure 8). The deduction of the T_{la} parameter is easy. However, it remains the choice of the rays which will be used for the R_{sp} inversion. Only two rays should be necessary. But, there are many quadruplets of rays available. In order to verify the robustness of the method, inversions have been processed on several possible pairs of rays. The first part of the signal being composed of direct arrivals, the first usable quadruplet is the quadruplet marked *qu*1 on Figure 8. The last quadruplet, which is in the vicinity of the critical angle, is not taken.

Finally, the case of two rays inside the same quadruplet is not considered. As we want to perform the inversion on low angle rays, there are three possible families of choices:

- The first beam is taken in the quadruplet *qu*1, the second being taken in any quadruplet *qu*3, *qu*4, *qu*5 or *qu*6 (64 possibilities)
- The first beam is taken in the quadruplet *qu*2, the second being taken in any quadruplet *qu*4, *qu*5, or *qu*6 (48 possibilities)
- The first quadruplet is taken in the quadruplet *qu*3, the second being taken either in *qu*5 or *qu*6 (32 possibilities)

This procedure produces a representative sample of 124 doublets on which the robustness of the inversion against the noise of the amplitudes and influence of the incident angle can be tested.

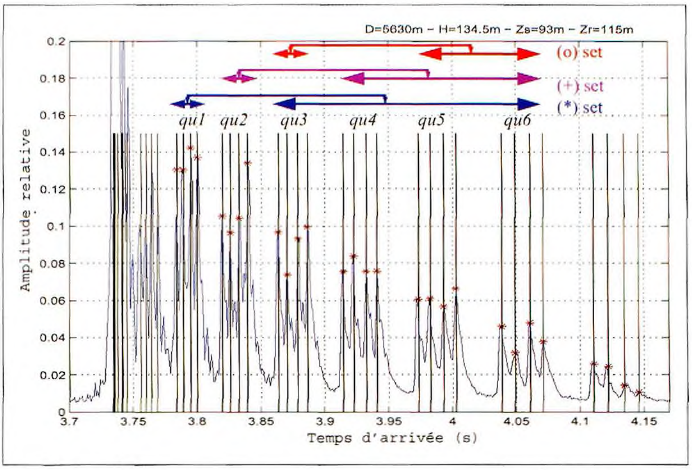

Figure 8: Comparison of the medium response and the traces of the real rays. There is a perfect correspondence between the predicted beams and the reflected beams. There are many combinations to choose two rays among the number of arrivals. Three solutions families have been tested: choice of a beam in qu3, and in qu5 or qu6, choice of a beam in qu2, and in qu4, qu5, or qu6, choice of a beam in qu1, and qu3, qu4, qu5, or qu6

2) Inversion

The first step of the inversion is to estimate the compression velocity. It is straightforward to obtain using the measure of the arrival time of the last ray, as reported in Eq (8).

The density is then deducted through Eq. (3).

The second step of the inversion is to estimate the ray amplitudes for the set of selected doublets.

This estimate is done by detecting of the maximum during a time span centred on the mean arrival time of the considered beam. At this stage, the R_{sp} amplitude is balanced according to the state of the sea and according to the geometrical dispersion.

Configuration	D = 5630m	H = 134.5m	Zs = 93m	Zr = 115m	C_{moy} =1511.5ms $^{-1}$	
Step 1	T_{la} = 4.15 s					
Inversion Step 1	**C_b = 1685 ms^{-1}**			ω= **1.87 kg/dm^3**		
Step 2	y_1 = 0.1303 y_2 = 0.0967	t_1 = 3.784s t_2 = 3.8637s	ω_1 = 11.5deg ω_2 = 16deg	$p(\omega_1)$ = 3 $p(\omega_2)$ = 5	q_1 = 2 q_2 = 3	D 1 = 5721.5 D 2 = 5840.7
Inversion Step 2	ω_b = **0.7634 d $\tilde{B}$ω**					

Table 1: Parameters and results of the inversion for a ray doublet (first beam of qu1, last beam of qu3)

Step 1	Step 2	
C_b = 1685 ms^{-1}	Set 1 (64 couples)	ω_b = 0.98 dB/l
	Set 2 (48 couples)	ω_b = 0.77 dB/l
ω = **1.87kg/dm^3**	Set 3 (32 couples)	ω_b = 0.67 dB/l
	Mean	ω_b = 0.81 dB/ω

Table 2: Mean results of the inversions on all the data (124 ray doublets)

The compression attenuation is then estimated through the Eq. (17).

3) Results

An example of inversion is presented in Table 1. All the results are given in Table 2 (mean results) and displayed on Figure 9. In a data set, the dispersion around the value of the compression attenuation is mainly due to the aberrant data (erroneous amplitudes).

Such anomalies are possible due to noise or bathymetry effect which can locally affect the energy (presence of algae or outcropping rock...). However, the mean values are reliable. It seems that the mean value is a little different for the low angles than for the high angles. This can be caused by surface reflection effects or by a divergence in the experimental model of the fluid reflection model of Rayleigh.

The shear effect, for example, can increase the attenuation of the low angle rays and decrease it for the high angle ones. The results accepted for this study are the ones given by the mean value, i.e. α_b = 0.81 dB/λ.

In conclusion, this method has allowed the determination of the geoacoustic parameters of the medium equivalent to the real bottom encountered in the north-south configuration of the INTIMATE96 experiment. These parameters are:

$$C_b = 1685 \text{ m/s}, \alpha_b = 0{,}81 \text{ dB}/\lambda, \rho_b = 1{,}87 \text{ kg/dm}^3 \quad (18)$$

The comparison of the reflection coefficients for the equivalent medium and for the real bottom is excellent for the subcritical angles, as shown on Figure 10.

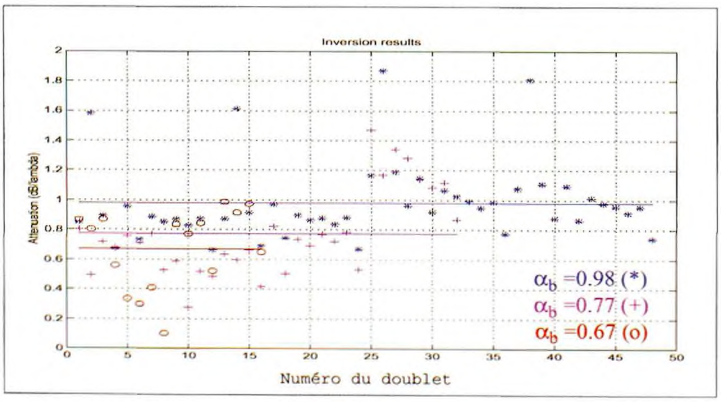

Figure 9: Resulting inversion for the compression attenuation for all the three sets of data. The mean value is given by the solid line

4.3. Discussion

The object of the method proposed by this work is to estimate the geoacoustic parameters of a medium equivalent to the real bottom. The results of the INTIMATE96 experiment show that this method is very simple to set up, that it is rapid, precise and robust. The losses calculated for the equivalent medium are the same as for the real bottom since the difference between losses are lower than a few tenths of decibels over a length of 10km. One of the advantage of this method is that it is based on the analysis of the impulse response (which only needs one receiving hydrophone) and on the propagation of the bottom and surface reflected rays. It is then not very sensitive to the velocity conditions within the water column. The instrumental procedure is also very light as it only needs a non-calibrated wide band source and a single hydrophone. The accurate positioning of the sensors is not necessary, and the method is not sensitive to the movement of the source or receiver. It is also stable for different water depths.

The main limitations of this method can be outlined as:

- At present it is only valid for a range independent environment. The reflection coefficients have so far only been developed in that case. However, the first results (non available here) show that the case of a medium with a variable bottom type could be treated simply by an equivalent medium vertically (sedimentary layers) as well as horizontally (breaking zones)
- The effects from the surface can be disturbing, as the last ray can be lost in the noise, especially when the sea state reaches 4. Below that state, it is possible to filter the noise from the surface reflection effects by using standard relations
- The method requires a sufficient signal to noise ratio, which gets more difficult over long distances. On the other hand, over short distances, the number of reflected beams can be insufficient to allow the determination of the subcritical zone of the reflection coefficient. There is then an optimum distance range, depending on the frequency and on the water depth, for which the method is applicable. However, this interval is large enough to insure the stability of the method and allow the use of sonar sources, which have relatively high frequency ranges and an interesting signal/noise ratio
- The method is not applicable to highly absorbing media, for which the stable part of the signal is very weak. However, it also means that the interesting part of the signal will be the one around the low angles (typically less than 10°). The method will however tell that the bottom is highly absorbent which can be pertinent operational information

5. Conclusions

A simple and practical approach for the geoacoustic inversion has been presented in this paper. The principle of the method is to estimate an equivalent medium which will have the same acoustic propagation properties as the real medium. It is based on the processing of wide band signals received on a single hydrophone. This method has successfully been applied to the INTIMATE96 experiment data. Limitations have been assessed and none of them appear overwhelming for the set-up of an operational system.

The continuation of this work would lie in two directions: first, it would be interesting to study the possibility of extending the concept of inversion by equivalent medium to more complex environments, like variable bottom-types and variable bathymetry. The data set necessary for these studies has been collected on the Armorican continental shelf during the INTIMATE98 experiment (Stéphan, et al, 2000). Second, it would also be interesting to study the operational feasibility of this approach in the frame of rapid environmental evaluations. In particular, can the existing sonar systems be used in this approach to provide a fast, robust and accurate measurement of the acoustic losses due to bottom reflection in an unknown environment?

Such an approach, if possible, would significantly improve the knowledge of the environment to improve performance predictions of very low frequencies sonars. Finally, this method could potentially be interesting for adaptive

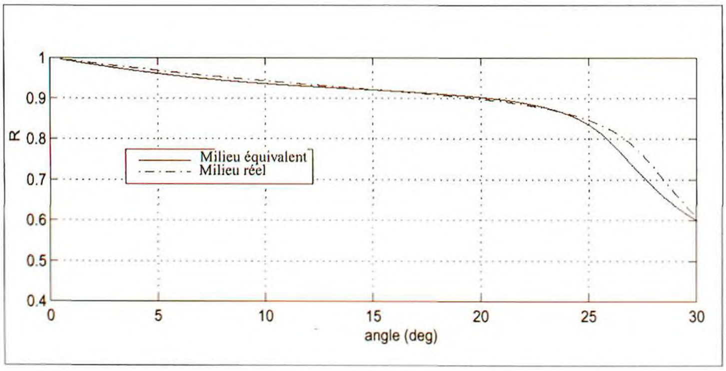

Figure 10: Comparison of the reflection coefficients for the equivalent medium and the real medium

sonar applications, where the estimate of the parameters of equivalent bottoms optimises the algorithms for detection and tracking of sources and targets.

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