Proceedings of the Fifth European Conference on Underwater Acoustics, ECUA 2000
Edited by P. Chevret and M.E. Zakharia
Lyon, France, 2000

ESTIMATING EQUIVALENT BOTTOM GEOACOUSTICAL PARAMETERS FROM BROADBAND INVERSION

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A simple and fast approach to retrieve equivalent geoacoustic parameters is presented in this paper. The method is based upon the processing of 300-800 Hz broadband signals on a single hydrophone.Two stable characteristics of the impulse response of the shallow water waveguide are estimated: the time dispersion and the bottom reflection amplitudes. This two features are analytically linked to the compressional speed and to the attenuation coefficient of the medium. The inversion of the two latter geoacoustic parameters is straightforward since it relies on an analytical expression. The method is tested on INTIMATE96 data. The results show an excellent agreement between the reflection of the true medium and the reflection coefficient of the equivalent medium.

1. INTRODUCTION

Acoustic inversion can lead to good estimates of the bottom geoacoustic parameters, especially when very low frequencies are used. Bottom models can also be built as equivalent media, which means that the estimated medium behaves as the true medium in the limit of the acoustic application (frequency, aperture). Of course, such an approach may be totally unadapted for geophysical characterization since the equivalent medium may not be physically relevant. However, the major advantage of the equivalent medium approach is that it allows the assessment of most important parameters consistently with the sonar systems. On the other hand, a new trend in geoacoustic inversion lies in the use of broadband acoustic signals received on sparse arrays, possibly reduced to a single hydrophone [1]. The bottom properties can be robustly and efficiently retrieved from the time dispersion and the attenuation of the amplitudes of bottom-reflected rays [2]. However, the inversion process still relies on a few hundred runs of the forward model.

In this paper, we combine the broadband inversion concept with the equivalent medium concept. This approach is based upon analytical developments of the reflection coefficient to retrieve the equivalent medium properties. Such a method avoids intensive computations. This approach is tested on the INTIMATE96 data set, which consists in broadband signals between 300 and 800 Hz.

2. THE INTIMATE'96 EXPERIMENT

The main objective of the INTIMATE project is to monitor internal tides by use of acoustic tomography [3]. However, data exploitation, based upon broadband signal processing on a single hydrophone, turned out to show that several other issues could be efficiently adressed including source tracking [4] and geoacoustic inversion, which is treated in this paper. The first exploratory experiment of the project, called INTIMATE96, was carried out in June 1996 on the continental shelf off the coast of Portugal. A broadband acoustic source, towed from the oceanographic vessel D’ENTRECASTEAUX, and a 4-hydrophone vertical array were used. Acoustic data were collected for 5 days, including legs where the source ship was moving and legs with the ship on station. The signals received on the phones were transmitted and processed aboard the Portuguese hydrographic vessel NRP ANDROMEDA for real time analysis. Intensive environmental surveys (including corings and seismic survey) were also conducted to evaluate the sedimentogical bottom structure. The emitted signal is a Linear Frequency Modulation (LFM) chirp from 300 to 800 Hz. The chirps lasted for 2 seconds and were repeated every 8 seconds. The acoustic signal are pulse-compressed by cross-correlating each received sequence with the emitted signal replica. All sequences are lined up on the leading edge to filter out instrument position fluctuations. A typical sequence of data is represented in Figure 1. The environment of the experiment along a range independent track is given in Figure 2. The received sequence is divided in two parts. The first spike consists in direct paths refracted in the thermocline with a few number of bottom reflection, highly sensitive to the sound speed profile. The second part, quite stable, exhibits a textbook multipath structure, composed with surface and bottom reflected rays.

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Fig. 1: Typical INTIMATE’96 sequence of data (averaged on 10’ min).

3. GEOACOUSTICAL FORWARD PROBLEM

The three-layers geoacoustical model described in Fig. 2 is not adapted to geoacoustical inversion due to the large number of parameters which have different impact on the measured acoustic field. It is interesting to note that for most of sonar applications, predicting detection ranges mainly relies on the ability to estimate transmission loss for small grazing angles. In that sense, the Rayleigh reflection coefficient $R(\theta)$ is an efficient bottom describer for acoustic propagation purposes: $R(\theta)$ has two parts bounded by the critical angle. Rays whose grazing angles are smaller that the critical angle are propagated in the water column with a loss proportional to the pre-critical part of R. At a given frequency, for most of cases (even for complicated seabed), the typical shape of the pre-critical part of R can be parametrized by a semi infinite fluid layer, i.e. the equivalent bottom.

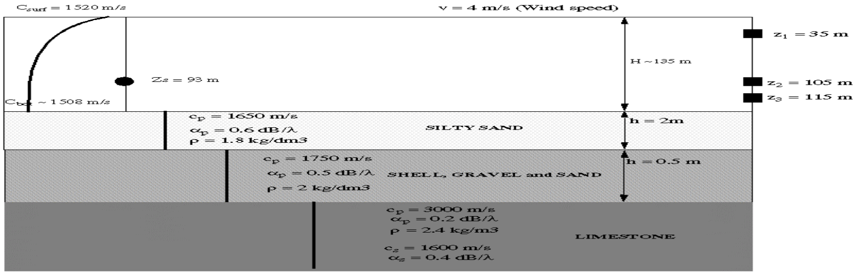

Fig. 2: Experimental set up and environment parameters in the range independant leg.

Considering a semi-infinite fluid medium, the last arrival is related to the critical angle i.e. to the compressional sound speed of the equivalent medium. The amplitude of a single ray decreases with its time of arrival (or equivalently the grazing angle) giving a sample of the reflection coefficient value (related to attenuation) at power *n*, *n* being the number of bottom bounces. If it is possible to obtain experimentally the time dispersion and the attenuation law (filtered from the surface reflection losses), a rather straigtforward inversion will be possible to determine the compressional speed of the bottom and the attenuation coefficient of the equivalent medium. The previous analysis is valid at a single frequency. One can argue that the use of broadband signal is not consistent with the fact that the reflection coefficient depends on frequency. In fact, the analysis can be carried out for several frequency ranges, in which it is considered that the equivalent medium is valid.

The objective is to formalize the relation between the reflection coefficient and the impulse response. The Rayleigh reflection coefficient of a fluid-fluid interface is:

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

with $Z_i = p_i.c_i/\sin\theta$, where i stands for b and w, respectively for the bottom and the sea water. The term c_b, complex formulation of the bottom velocity, is a function of the compressionnal speed C_b (m/s) and the attenuation α_b (dB/λ) expressed as $c_b=C_b/(1+i\alpha_b/2\pi 8{,}686)$. The bottom density is a second order parameter for propagation signals since it mainly affects the low value of R. An approximated value of ρ_b will be deduced from C_b using the Hamilton relation, valid for continental terrasse sediments [5], $C_b=2330{,}4-(1257.\rho_b)+487{,}7.\rho_b^2$.

$R(\theta)$ finally depends on 2 parameters, α_b (in dB/λ) and C_b(in m/s). The next step is to characterize the impulse response with two parameters: the last arrival time T_{la} and a spike amplitude $y_{obs}(\theta_i)$. If the source level and the hydrophone sensitivity are unknown, it is preferable to define the ratio :

$$Rsp_{i,j} = \frac{y_{obs}(qi)}{y_{obs}(qj)} \qquad (2)$$

We therefore make the assumption of a linear trajectory for the surface-bottom reflected rays, easily justified by calculation. Using $D_{la} = T_{la} .C_{moy}$ and writing the critical angle as $\theta_c = \mathrm{acos}(D/D_{la})$, the last arrival time is simply related to the geoacoustic parameters C_b by $T_{la} = D.C_b/C_{moy}^2$, C_{moy} being the water column averaged sound speed value, D the range between the transmitter and the receiver, D_{la} the linear trajectory of the ray reflected at the critical angle. To relate R_{sp} and α_b, we need to recall the amplitude of a given ray reflected on the bottom. It is theoretically expressed as :

$$y(qi) = \frac{\sqrt{\cos(qi)}}{D_i} \cdot e^{-aDi} \cdot \left|R_s\right|^{p(qi)} \cdot \left|R_b\right|^{q(qi)} \tag{3}$$

The first term is the geometrical dispersion (under a linear trajectory hypothesis), the second term is the volumic attenuation (α dB/km/Hz is the Thorp coefficient, and D_i the linear trajectory of the ray), R_s and R_b are repectively the surface and bottom reflection coefficient modulus (p and q being the number of reflection on surface and bottom).

Fitting the impulse response with a single basic eigenray calculation, we easily relate each spike with the arrival time of the corresponding eigenray. For a given spike, we therefore use eigenray parameters : θ_i, p, q, D_i . $|R_s|$ is estimated from the wind measurement using standard laws. We then obtain for R_{sp}:

$$R_{sp} = \frac{D_1}{D_2} \cdot \sqrt{\frac{\cos(q_2)}{\cos(q_1)}} \cdot \frac{\left|R_s\right|_2^{p2}}{\left|R_s\right|_1^{p1}} \cdot \frac{\left(\left|Rb\right|_2^{2}\right)^{q2}}{\left(\left|Rb\right|_1^{2}\right)^{q1}} = Cte \cdot \frac{\left(\left|Rb\right|_2^{2}\right)^{q2}}{\left(\left|Rb\right|_1^{2}\right)^{q1}} \tag{4}$$

An analytical expression linking α_b and R_b is then necessary to calculate α_b from R_{sp}.

We have developed an asymptotical expression of R_b valid below the critical angle. The coefficient R_b can be written as:

$$\left|R_b\right|^2 \approx \frac{1 - v \cdot a_b}{1 + v \cdot a_b} \quad \text{with} \tag{5}$$

$$v = \frac{2 \cdot r_b'}{\left(1 + r_b'^2\right) \cdot (A-1) \cdot 2.p.8{,}686}, \quad A = \cos(q_i)^2 \cdot \frac{C_b^2}{C_w^2}, \quad r_b' = \frac{\sin(q_i) \cdot \frac{C_b}{C_w}}{\sqrt{A-1}} \cdot r_b \tag{6}$$

This asymptotic expression gives remarquably good results (except for very smooth bottom) from $\theta_i = 0$ until $\theta_i < \theta_c$. This system basically express the forward geoacoustic problem for the equivalent medium.

4. GEOACOUSTICAL INVERSION

Under weak constraints, it is possible to have a simple formulation of the forward model. It yields an analytical formulation of the inverse problem which can be stated as follows:

$$C_b = f^{-1}(T_{la}) = \frac{C_{moy}^2 \times T_{la}}{D} \tag{7}$$

from which we deduce ρ_b . Knowing C_b and ρ, we calculate

$$a_b = g^{-1}(R_{sp}) = \frac{R_{sp} - Cte}{(q_1 v_1 - q_2 v_2) \cdot (R_{sp} + Cte)} \tag{8}$$

q_i being half the number of bottom bounce and v_i calculated by eq. 5 for the ray defined by θ_i. Cte is calculated from eq. 4. INTIMATE'96 acoustical data set is split in three different phases. The first phase consists in a 25h station with a flat bottom, following a North-South direction which is perpendicular to the presumed direction of propagation of the internal tide. This allows to assume a range independant environment. We extracted a 30-minutes data set from this station to test the inversion procedure. An incoherent treatment is done over 75 pings corresponding to a 10-minutes average. The inversion being based on T_{la} and R_{sp} measurement, we have as much inversion result (for α_b) as multipath spike couples (defining

R_{sp}). We consider every couple. Consequently, we used 3 data set of spike couple to get R_{sp}, leading to 3 inversion sets. The first step of the inversion is then processed and gives an estimate of the compressional speed C_b using eq. 7. The density ρ_b is then deduced from C_b. Each spike of the impulse response is then parametrized by it corresponding eigenray characteristic (fig. 3). Applying eq. 8, we deduce α_b. Full results are presented in fig 4.

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Fig. 3: Superposed plot of eigenray calculation and data impulse response.

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Fig. 4: Plot of calculated attenuation versus the 3 data set used fo the inversion. For each data set, solid line gives the mean value of a_b.

Within a data set, the dispersion of the attenuation estimate is mainly due to fluctuations in the spike amplitude, probably due to a noise effect or to bathymetric feature. Averaged values are more consistent even if a decrease is observed over the higher grazing angle range. This possibly be due to an experimental mismatch with the Rayleigh reflection model. The effect of shear waves, for example, would increase the attenuation for lower grazing angle and would decrease it for higher grazing angles. Then, it is preferiable to retain the averaged value calculated from the whole data set, i.e α_b=0.81 dB/λ. Inverted equivalent medium is finally defined by: ρ_b=1.87 Kg/dm^3, C_b=1685 m/s, α_b=0.81 dB/λ. As shown in Fig. 5, the comparison between inverted equivalent medium and the true medium reflection coefficient shows an excellent agreement within the precritical grazing angle range.

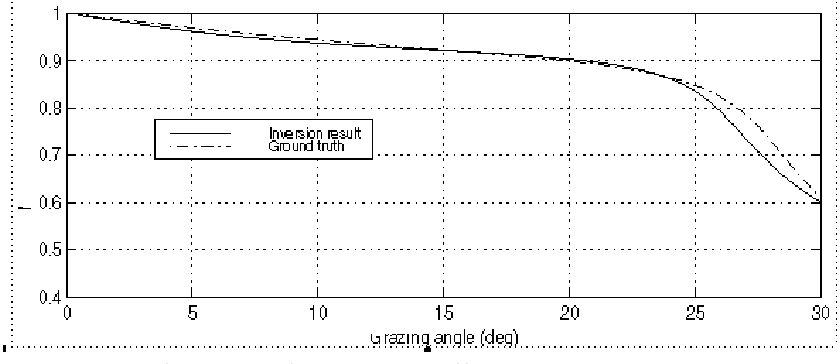

Fig.5:Reconstruction of the reflection coefficient in the equivalent medium and comparison with the true medium for sub-critical angles .

5. CONCLUSION

A simple and fast approach to retrieve geoacoustic parameters has been presented in this paper. The principle of the method is to invert for an equivalent medium which gives the same propagation features than the true medium. The application on INTIMATE96 data shows very good results. The same kind of work is in progress on different type of bottoms (data were collecteted duting the INTIMATE98 experiment). Possible applications of the method could lie in operationnal acoustic REA as well as in Environment Adaptive Sonar technology.

6. ACKNOWLEDGEMENTS

The partners of the INTIMATE project wish to thank the staff of NRP ANDROMEDA, the staff of BO D'ENTRECASTEAUX and people of Mission Océanographique de l'Atlantique (aboard D'ENTRECASTEAUX). We also wish to thank the SACLANT Undersea Research Center for lending the Portable Array System and Roberto Chiarabini (SACLANTCEN) for his participation in the array preparation, deployment and use. Thanks to T. Folegot and G. Bonnaillie (CMO) for their active contribution in this work. The study was jointly sponsored by SHOM (exploratory program 95901), the Portuguese Ministery of Research (PRAXIS XXI) and ONR (contract N00014-95-1-0558).

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