ESTIMATION OF SEDIMENT ACOUSTIC PROPERTIES FROM HORIZONTAL ARRAY DATA

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Abstract: *Oil companies conduct geophysical survey in different parts of the world. While the analysis conducted by them is directed towards determining the presence of oil in the deeper layers of the sediment, information on the shallower sediment layers that the data contains is generally ignored. In this paper we investigate the possibility of estimating the sediment properties from such data. The inversion is performed using both linear and non-linear methods. The performances of these methods are compared based on the correlation between the fields predicted by the models and the measured field.*

Keywords: *Linear and non-linear inverse, Sediment acoustic properties, horizontal array data*

1. INTRODUCTION

Oil companies conduct geophysical surveys routinely in aid of oil exploration. The data are collected on horizontal arrays. The analysis conducted by the oil companies are directed towards determining the presence of oil in the deeper layers of the sediment. But the data contains information on the acoustic properties of the shallower layers of the sediment also, and this information is useful in predicting the propagation of sound in the water column.

In this paper we explore the possibility of extracting the sediment acoustic properties from such data. The particulars of the source, receiver array and other details furnished by the survey agency are listed below.

1. Source: Bank of air guns with its centroid of the air-guns at a depth of 6 m from the ocean surface.
2. Receiver: Array length = 2375 m. The closest receiver at 200 m from the source. Receiver depth = 6 m. The receiver array had negligible distortion and was assumed to be perfectly horizontal.

3. Inter-element distance = 25 m
4. The depth of the water column was given as approximately 35 m.
5. No information on the location (i.e. latitude /longitude) was provided.
6. Source signature is not known.
7. Sampling rate = 500 Hz.
8. 3 seconds of data recorded at each channel.
9. The data acquisition system was designed to trigger the source and receiver simultaneously

Three horizontal array data sets have overlapping region, shot 95 data is from 0m to 2375m, shot 50 data is from 1125m to 3500m, shot 5 data is from 2250m to 4625m.

The signal received at one of the hydrophones is shown in Figure 1. The spectrum of the signal is also shown in the figure. The signal is wide band with significant energy in the band 10 Hz to 50 Hz..

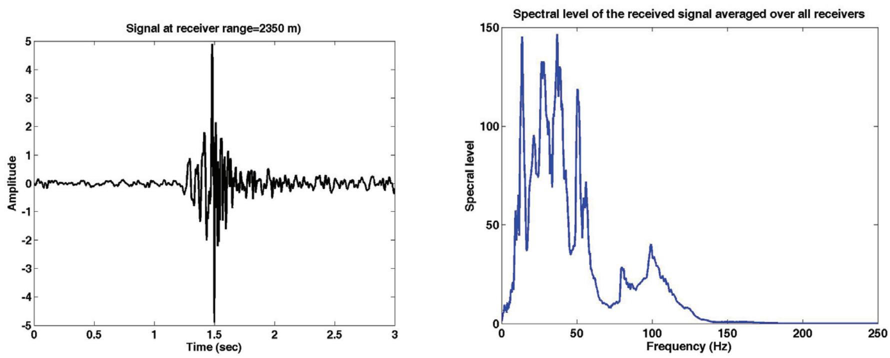

Figure 1. The signal received at one of the hydrophones on the horizontal array and its spectrum

The signal at each receiver located at distance r from the source is a time series $P(t, r_n)$ where P is the pressure field, t is the time. A Fourier transform of this time series will yield $p(\omega, r_n)$. Therefore by performing the Fourier transform of the signal acquired at each hydrophone we obtain the pressure field as function of range at a discrete set of frequencies. The horizontal array data thus obtained can be used to estimate the acoustic properties of the sediment layers. The schemes that have been used to estimate sediment properties from similar data are:

1. Global optimization methods (non-linear methods) such as simulated annealing[1-2] and genetic algorrithms[3-4]and
2. Linear methods such as those based on modal eigenvalues[5,6].

In this paper we present results obtained from both these methods. Among the non-linear methods, we chose one that is based on genetic algorithm.

In global optimization approach, the inverse problem of obtaining the sediment properties from the field measurement is cast as an optimization problem where a cost function is minimized. Let $p_{obs}(\omega, r_n)$ be the pressure field at frequency ω and receiver location r_n.
We now assume a model which characterizes the acoustic properties of the sediment layers and calculate the pressure field at the receiver locations for the given frequency. Let this be $p_{cal}(\omega, r_n; m)$. In this m is a parameter vector that describes the sediment acoustic properties. The cost function $\phi(m)$ is then defined as

$$\phi(m) = \frac{1}{K}\sum_{i=1}^{K} \bar{p}^{*}_{cal}(\omega_i)\bar{p}_{cal}(\omega_i; m)$$

In the above expression $\bar{p}$ is a vector of the complex pressure field at the receiver locations, (*) represents the complex conjugate and K is the number of frequencies. The cost function as defined above is maximized and the parameter vector that gives the maximum correlation is the solution to the inverse problem.

To perform inversion using linear method, the modal eigenvalues were obtained from the wavenumber spectrum determined using the horizontal array data. Rajan et al[6] describe a method wherein the modal eigenvalues extracted from field data are used to estimate the sediment acoustic properties.

2. GLOBAL OPTIMIZATION METHOD

Geometrical and geoacoustical parameters were estimated by Matched Field Processing technique[3,4] using the genetic algorithm. Since there was no a priori information about ocean bottom, the eigenvalue structure was used to get a basic model. Spacing between eigenvalues at a given frequency and difference between the eigenvalues of the same frequency contain information which is useful for modeling the ocean bottom. Proper modeling of ocean helps in reducing the parameter search space. We have considered a model consisting of 3 layers of sediment over a homogeneous half space. Within each layer, the compressional wave speed varies linearly with depth, while the density and attenuation do not vary. The effect of shear waves on the acoustic data is assumed to be negligible, and is therefore ignored. The parameter search range for the basic model is given in Table 1.

Parameter	Thickness (m)	Sound speed (m/s) at layer top	Sound speed gradient	Density (gm/cc)	Atten. (dB/λ)
Water	30-38	1520-1545	0-(-0.15)	1	0
Sed.Layer 1	35-75	1600-1650	0.7-0.1.3	1.6-1.8	0.05-0.2
Sed.Layer 2	20-70	$c_{2t} = c_{1b}+$ $(0-100)$	0.5-1.0	$\rho_2 = \rho_1+$ $(0-0.1)$	0.05-0.2
Sed.Layer 3	100-200	$c_{3t} = c_{2b}+$ $(100-200)$	0.2-0.5	$\rho_3 = \rho_2 +$ $(0-0.1)$	0.1-0.2

Half space		$c_{hs} = c_{3b}+$ (50 – 200)		$\rho_{hs} = \rho_3+$ (0 – 0.1)	0.1-0.2

Table 1: Parameter search range for the basic sediment model. c_{nb} is the sound velocity at the bottom of n^{th} sediment layer, c_{nt} is the sound velocity at the top of n^{th} sediment layer, ρ_n is the density at n^{th} layer.

3. LINEAR METHOD BASED ON MODAL EIGENVALUES

The possible sources of error in the estimation of the eigenvalues from the data acquired on the horizontal array are:

1. Receiver motion
2. Sampling interval of 25 m. is too large even at the relatively low frequency of 25 Hz (approximately 60m. wavelength in water) A much smaller spatial sampling interval is desirable.
3. Short aperture
4. Error in location of the receivers (range and depth).

The receiver array is moving with a known constant speed . The effect of receiver motion was taken into account by making corrections to the eigenvalue obtained from the data and corrections to the range to each receiver. In order to sample the field at approximately 1/5 of the acoustic wavelength, we investigated the feasibility of interpolating the field obtained at 25 m range interval. The interpolating was done by slowing down the phase by multiplying the field by a factor exp(-ikr)there k is the wavenumber. After performing interpolation of the field with slowed phase, the interpolated field was multiplied by exp(ikr) to restore the phase. The accuracy of this scheme was tested with noise free and noisy synthetic data and it was confirmed that this scheme permits determination of the field at the required sampling interval.

The horizontal array has an aperture of 2375 m. This short aperture creates two problems in the determination of the eigenvalues. The size of the aperture of the horizontal array plays a critical part in the ability of this method to resolve closely spaced modes. Errors in the location of the peaks arise due to the leakage of energy between the modes. In order to overcome these deficiencies we estimated the spectrum using the procedure described in [5]. This method is based on spectral estimation using the AR model and in comparison to Music and Esprit[7] gave the best results.

The location of the receivers is not known exactly since the array is in motion. The error is both in the range and depth of the receivers. In [7] the impact of range error was studied and the error was quantified. It was shown that errors in range resulted in errors in the estimate of the eigenvalues with errors in the estimate of weak higher order modes being significant.

4. RESULTS OF INVERSION

A. Non-linear method

The motion of the array results in Doppler shift of the frequency. The times taken for the signal to arrive at the receivers vary and during this time the receivers have moved. These two errors were compensated for.

As indicated earlier, the acoustical and geometric properties of the water column were not measured during the survey. This was also estimated from the data. The sensitivity of the acoustic field to variations in the water parameters, namely, the sound speed profile in water and channel depth is greater than its sensitivity to changes in the geoacoustic parameters. It is therefore desirable to obtain good estimates of sound speed profile and channel depth before estimating geoacoustic parameters. Since the channel depth is about 35 m, the water sound speed is assumed to have a small gradient. Higher frequencies (> 80 Hz) were used to estimate channel parameters. Acoustic field sampled by sensors 70-95 were used to cut down influence from deeper sediment layers. Five Frequencies with a difference of 5 Hz in the interval (85 to 109 Hz) were used to get the estimates. Channel depth 36.7 to 37.2 and water sound speed 1536 to 1542 were obtained. This estimate was further refined by joint estimate of water column and sediment properties.

To estimate bottom parameters five frequencies from 17 – 50 Hz and 2 frequencies from 85 to 105 Hz were used. Figure 2 shows the models obtained using shot 95, shot 50, and shot 5 data. Correlation between the measured field and the model predicted field are given in Table 2.

The following features found in the data suggest that the ocean bottom in this area is range dependent.

(a) Estimates obtained for the three shots had significant differences.
(b) Wavenumber spectra for the three shots were different.
(c) The magnitude of the acoustic fields for the shots is different in the low frequency region (20 – 30 Hz).

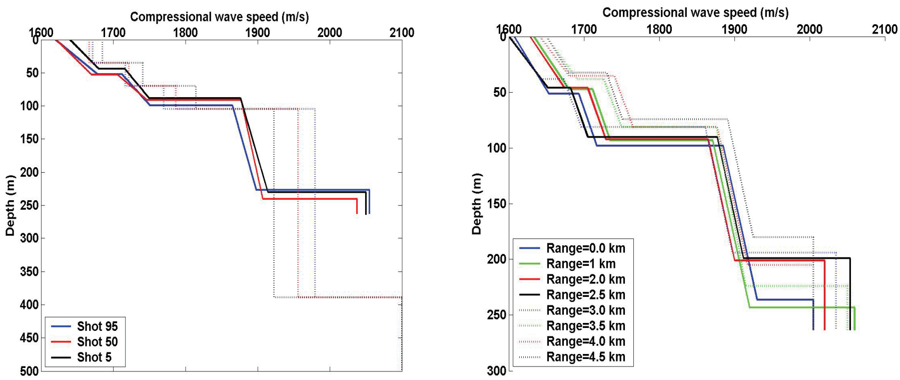

Figure 2: In the figure at left the compressional wave speed profiles (Range independent) obtained by non-linear inverse (genetic algorithm) and linear inverse (modal inverse) are compared. Full lines are from non-linear inverse and dotted lines are from linear inverse. The figure at right shows the result of range-dependent inverse performed using genetic algorithm. The compressional wave speed profiles at different ranges are presented with shot location of shot 95 considered as zero range.

Frequency Band (Hz)	Shot 95	Shot 50	Shot 5
15-20	0.84	0.81	0.82
20-30	0.84	0.81	0.81
30-40	0.76	0.75	0.81
40-45	0.70	0.62	0.65

Table 2: Correlation between the field predicted by the model and the measured field at receivers at ranges 1425 m to 2550 m.

To get a range dependent model, all the three data sets were considered together. Eight different segments were used. The parameter search space was chosen around the range-independent model. Model field was calculated using the adiabatic mode theory. The prolfiles at eight locations are shown in Figure 2.

B. Linear method

Inversion based on modal inverse method[6] was performed using data from three shots (Shot 95, Shot 50, and Shot 5). Modal eigenvalues were extracted from the data sets by first obtaining the pressure at a given frequency from the broad band data acquired at each receiver. The pressure field extracted was interpolated to give the field at a required spatial sampling rate. The modal eigenvalues were then obtained using a high resolution wavenumber estimation method described in [5]. Noise in the data and the short aperture of the horizontal array introduces error in the estimates of the weak higher order modes. Because of this eigenvalues of the strong lower order modes were used as data in the inversion. Inversion was performed using eigenvalues estimated for five frequencies i.e., 18, 20 ,25, 30 and 35 Hz. The inversion was performed only for the compressional wave speed in the sediment. The sediment was assumed to be a fluid i.e. shear in the sediment was ignored. Further, a constant value of sediment density (1.7 gm/cc) and attenuation of 0.1 dB/acoustic wavelength were assumed. Since the water column depth and sound speed were not measured during the survey, the inversion includes estimation of the water column properties as well. The estimate of the water column depth was 39 m and the sound speed was 1542 m/s. Figure 2 shows the compressional wave speed profile in the sediment obtained for the three shots. In Table 3 we present the correlation between the experimental data for the 3 shots, and the field predicted by the model at all the frequencies.

Frequency (Hz)	Shot 95	Shot 50	Shot 5
18.0	0.74	0.80	0.84
20.0	0.87	0.76	0.82
25.0	0.72	0.78	0.78
30.0	0.65	0.71	0.70
35.0	0.59	0.51	0.59

Table 3: Correlation between the experimental data and the model predicted field computed at receivers at ranges from 1500 m to 2000 m.

5. DISCUSSION AND CONCLUSIONS

Table 2 shows that the correlation values attained using the genetic algorithm is approximately 0.8 in the frequency bands up to 30 Hz and slightly lower at higher frequencies. A similar behavior is seen in the correlation values obtained using the modal inverse method. However the correlation values for the modal inverse method are smaller than those for the other method. These differences in performance are, at least partly, attributable to the following reasons.

1. The model inverse method used a much simpler bottom model namely isovelocity layers. The attenuation and density in each layer and in the half space were assumed known and were prescribed values based on the nature of the sediment.
2. In the method using genetic algorithm estimates for a much larger number of parameters were obtained. The sound speed in each layer was assumed to linearly increase with depth. The density and attenuation in each layer and source and receiver depths were also taken as parameters to be estimated.
3. The genetic algorithm maximizes the correlation between the measured field and the field predicted by the field.
4. Only the strong lower order modes were used in the inversion.

The compressional wave speed profiles obtained by both approaches have a similar structure up to a depth of 100 m. Beyond this depth the values obtained by the two methods are considerably different. We are of the opinion that this is because only the strong lower order modes were used in the inversion.

The range dependent profiles show substantial variability in the depth interval of 0 m to 100 m. Use of the range dependent profile resulted in some improvement to the correlation values.

6. ACKNOWLEDGEMENTS

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