Rapid and robust single receiver geoacoustic inversion in shallow water

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Abstract-Estimating geoacoustic parameters is important for many applications in underwater acoustics. Conventional techniques generally employ vertical or horizontal receiver arrays whose output is matched field processed to invert for bottom parameters. Recent work has investigated whether the receiver array could be replaced with a single receiver with a moving source creating a virtual source array. This paper presents a new technique applicable to shallow-water geoacoustic inversion based on a moving source and a single stationary receiver. In contrast to other single receiver geoacoustic inversion methods, we use the multi-path structure of the signal to create a virtual vertical array to estimate the source-receiver geometry. Since the source is moving we effectively create both an incoherent synthetic horizontal source aperture and a coherent synthetic vertical aperture by means of the multipath. This method can be used to obtain the sound speed and density of the superficial seabed both quickly and inexpensively.

To provide multipath resolution, we use a linear frequency modulated signal varying between 1.5-5.5 kHz. Applying a Wigner-Ville transform to the received pulse train and stacking the result gives estimates of the time lags between the arrivals, permitting the multi-path structure to be determined. An inverse Wigner-Ville transform of the isolated direct arrival provides an estimate of the matched filter required in the time domain to estimate transmission losses for each path. Once the source-receiver geometry is estimated from the multipath structure then the angles of arrival for the bottom interacting paths can be computed. The inversion of bottom parameters (density and compressional sound speed) is performed by optimising an objective function that makes use of the angular-dependent reflection coefficient derived from the amplitudes of bottom-interacting paths, given the direct arrival amplitudes and path lengths. Data from experiments conducted in local Singapore waters and the geoacoustic inversion results will be presented.

1. INTRODUCTION

Acoustic propagation in the shallow water is influenced by several environmental factors including surface conditions, water column sound speed properties, bathymetry and seabed type. Among these factors, seabed often has the strongest effect on propagation and its properties are probably the most difficult to obtain. In order to predict the sound field, which is of interest to both scientists and sonar designers, the geoacoustic properties of the seabed should be known as accurately as possible. So far, the technology of the geoacoustic inversion has been accepted as a cost effective solution to estimate the seabed geoacoustic properties over direct measurement like ground-truth.

The description of experimental setup and some results using real data in local water will be introduced in the following sections.

2. GEOMETRICAL CONFIGURATION AND EXPERIMENTAL SET-UP

The trial took place in the southern islands of Singapore at a quiet shipping anchorage.

The experiment setup consisted of a fixed vertical array and a research vessel carrying the source.

Though the method uses a single hydrophone as the receiver, four hydrophones were deployed as a vertical array at depths of 2.5m, 6.0m, 10.0m and 13.0m as depicted in the fig 1. Later the sensor located at 6.0m was used in the calculations; since the multi path reflections is received in the order of direct path, surface reflection and bottom reflection. The data was acquired using the Hifdaq[1], a four-channel high frequency data acquisition system developed by ARL.

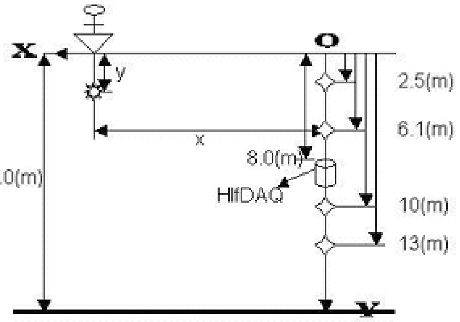

Fig 1 Geometry of experiment setup

Sound speed profiles were measured by deploying the CTD probe at 10 different positions along the track. As can be seen from the figs the maximum difference in the sound speed was approximately 1 m/s and therefore the sound speed profile was assumed a constant of 1540 m/s throughout the water column for modeling purpose.

By taking cores of the sea floor, the properties [material types, porosity and density] were collected from the locations of experiments. This is used as a ground truth for geoacoutic inversion experiment.

While slowly drifting at 1.4 knots (0.72m/s), the transducer on the boat sent out a Linear Frequency Modulated (LFM) signal with a frequency band 1.5kHz-5.5 kHz. The GPS coordinates where logged every time a signal was sent. During the trial, the boat made two runs. The signals reflected off the sea-bottom were collected by the Hifdaq and was stored in its hard disk. Later the data was read using a matlab program for further analysis and computation of the seabed properties.

3. SIGNAL PROCESSING AND ALGORITHMS.

Firstly, we separate the mixed signal into the direct, bottom reflected and surface reflected paths and calculate the time delay among the different paths by conventional matched filter; we obtained the reference signal in two ways.

By convoluting the original signal with the transducer's impulse response, this ignores phase. The result is shown in fig 2

By taking a time frequency transform of the received signal, and inverse transform of only the direct arrival. The Wigner-Ville transformation is used since it is optimal for LFM signals [2], and gives good separation between the arrivals as shown in fig3. An inverse Wigner-Ville transform that preserves phase does not exist however we use the inverse Wigner-Ville transform [3], which minimizes phase errors. The result of the inverse Wigner-Ville transform of the direct arrival is shown in fig 4. The envelop of the inverse transformed signal is good although some small errors are introduced caused by the extraction of the arrival.

The matched filter result is shown in fig 5.

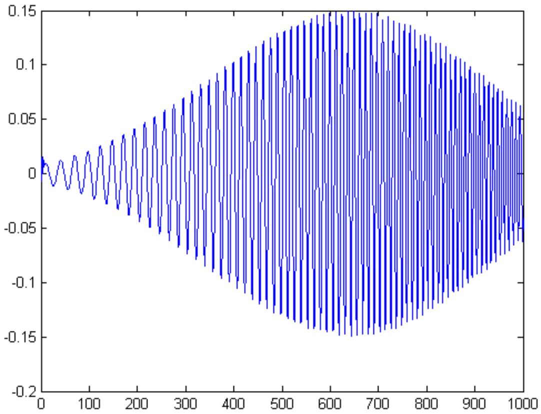

Fig 2 signal by convoluting the original signal with transducer's impulse response ignoring phase

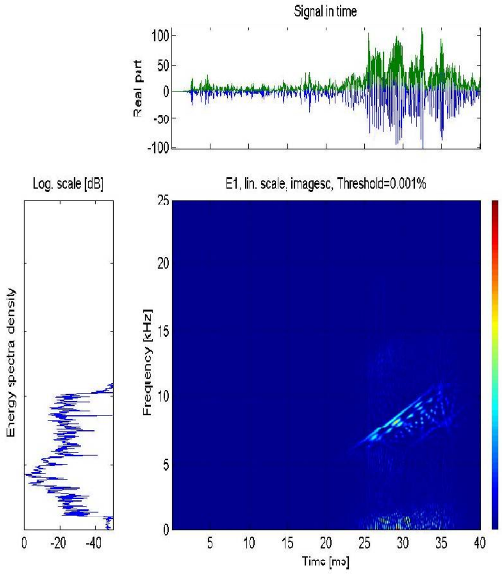

Fig 3 Time frequency distribution of multipath signal

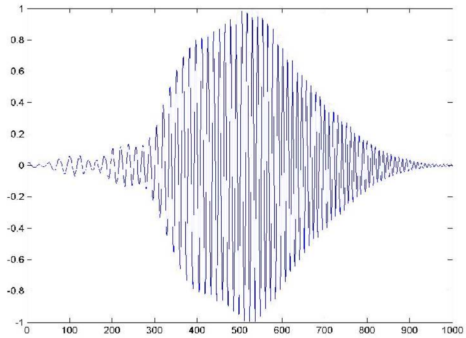

Fig 4 singal obtained by inverse wigner-ville transform

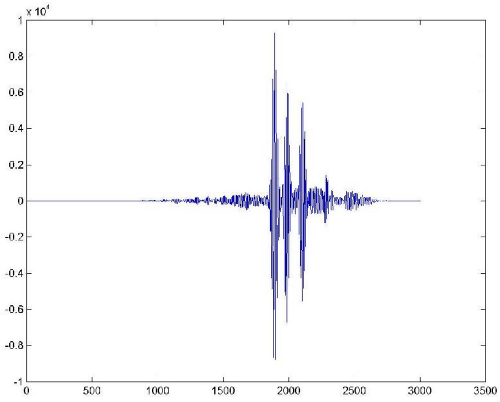

Fig 5 The matched filter result using the signal obtained by inverse Vigner-ville transform

We used the time difference of arriving (TDOA) method to calculate the source position or the range and water depth information. If we have the knowledge of the position of the source and sensors and geometry model of the experiment then we can obtain the incident angle of the bottom reflected path. The algorithm has been developed based on this assumption.

The surface reflected and bottom reflected signals could be assumed to be originating from two virtual sources (as shown in fig 6) so that we can use the conventional time difference of arriving (TDOA) method to calculate the unknown source positions.

We can extend functionality by estimating the horizontal range between source and Hifdaq and the water depth. This allows the algorithm to process the range-dependent geoacoustic inversion problem in a simple and rapid manner.

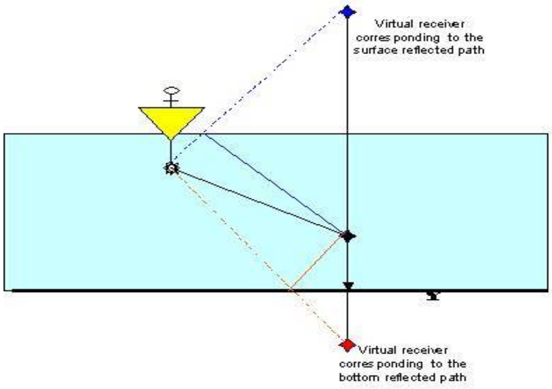

Fig 6 Source localized using multi-path

Using TDOA we can deduce the boat movement away or towards from the HiFDAQ from the differences in time lag between the surface-reflected and direct paths and the time lag between the bottom-reflected and direct paths. Both these values of time lag were found decreasing thereby confirming boat's movement was away from the HiFDAQ.

We chose three samples corresponding to the beginning, middle and end on the run. We calculated the position of the three samples and found them to be:

$X1$ = 56.9m, $y1$ = 6.1m.
$X2$ = 33.6m, $y2$ = 6.6m
$X3$ = 22.4m, $y3$ = 7.5m

Finally using the estimated source-receiver geometry and the time of arrival we can calculate the angle of incidence. We processed the all returns using the techniques described previously and the below fig 7 shows the reflection coefficients curve of the data. The sound speed of sea bottom is estimated from the critical angle, the bottom density can be obtained from the reflection coefficients curve by the least mean square estimation.

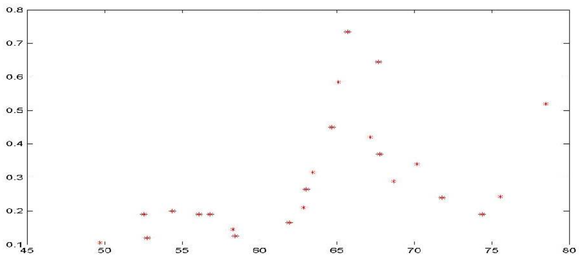

Fig 7 reflection coefficients samples from sample data

We calculated the position of the Hifdaq given the GPS positions of the sources along the track and compared it with the recorded GPS position. The difference between the new estimated position and original one is 14m and 9 m, see the below fig 8:

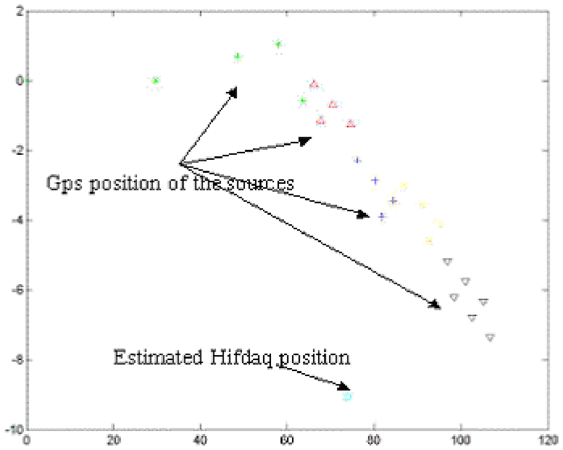

Fig 8 Estimated Hifdaq position using known sources'GPS position

4. RESULTS AND DISCUSSION

In local waters, the unconsolidated sediments are composed of silt, clay, shell fragments and gravel. From the core samples taken, the density was found to vary from 1.37gm/cm^3 to 1.84 gm/cm^3, but densities of most core samples are found to be between 1.60 mg/m^3 and 1.75mg/m^3. The porosity of the core samples fluctuates between 45% and 60%.

We estimated the sound speed and the density of individual samples using empirical formulae [4],[5],[6]. The sound speed calculated using the density and porosity of the bottom sediments is between 1590m/s and 1650m/s and the density is between 1.60 mg/m^3 and 1.75mg/m^3.

The value of compressional sound speed is C_p = 1603m/s and density is ρ = 1.46mg/m^3 using Geoacoustic Inversion. This is within reasonable limits as compared to the results obtained from actual samples.(C_p: 1590m/s~1650m/s, ρ: 1.60 mg/m^3 ~1.75mg/m^3)

We also inversed the geoacoustic parameters in the range dependent case, that the depth of Hifadq is assumed to be known. The inversed geoacoustic parameters are much closer to the result obtained by coring sample analysis than the above method. The results from this computation are given below.

C_p = 1693.3m/s
ρ = 1.5619mg/m^3.

The inversed depth of water column varies from 11.0253m to 12.0568m.

5. CONCLUSION

In this paper, we have shown that the single receiver geoacoustic inversion technique can be used to estimate the density and sound speed of the sea bottom. Moreover, this method fully implements the information of multi-path signal, which can further be used in source location and channel identification.

In this paper, we show that the multi-path signals can be separated by the time-frequency analysis and used to calculate the source positions from the time delays among the direct path, bottom reflected path and surface reflected path.

Finally, we obtained the estimate of the density and sound speed of sea bottom by matching the reflection coefficient curves from the theoretical model and that obtained from real data.

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