

Estimation of Sediment Properties Using Air Launched Sonobuoys

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LONG-TERM GOALS

The US Navy has been developing its Multi-Static Active Coherent (MAC) acoustic search system. MAC is an air launched acoustic search system that combines a newly developed coherent source sonobuoy with a field of receiver sonobuoys. With the introduction of the coherent source, operational search data collected during MAC exercises are well suited for post-processing to infer waveguide properties. The long term goal of this research is to investigate the feasibility of estimating sediment acoustic properties using data collected during such exercises.

OBJECTIVES

Modal dispersion data are used in inversion schemes that estimate sediment properties in range independent and range-dependent environments. The experimental scenario for the use of air launched sonobuoys to extract information about the sediment properties in the area covered by the sonobuoys is to have one of the sonobuoys broadcast a broad band signal with a large set of buoys receive these signals. These receiving sonobuoys will be dispersed over a wide area. In such an experimental set up the data acquired by the sonobuoys is used to estimate the sediment properties in the area covered by the sonobuoys. In March 2011, an experiment termed MOMAXV was conducted off the New Jersey coast. In this experiment broad band signals were broadcast from a ship carrying the source. The ship moved to discrete locations around a small set of free-floating buoys. This mimicked the situation where we have a near stationary sonobuoy with a source transmitting a broadband signals and a network of freely floating sonobuoys acquiring the transmitted signals. The objective of the current work is to analyze the data collected during the experiment and estimate the sediment properties of the region between the ship positions and the location of the sonobuoys.

APPROACH

A. Experiment details

MOMAXV was conducted between March 5 and March 18, 2011 off the coast of New Jersey. The complete details of the experiment are described in Frisk et al [1] which is devoted to analysis of narrow band data collected during the experiment. The experiment also included a broad band

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component in which ship towed a J-15 source and transmitted broad band signals from several discrete locations. At these locations the ship was near stationary. Three freely drifting buoys (Curly, Larry, and Moe) with hydrophones for recording signals were deployed before the start of the broadband experiment. The tracks of the ship and the buoys are shown in Fig. 1. The signal was an LFM sweep from 50 Hz to 300 Hz. To be able to get time synchronization, the transmitted signal from the ship was recorded in a hydrophone attached to the source frame. The signals acquired by Curly is used in the analysis to be presented in the following sections. There were 14 waypoints at which the ship was stationary and the broad band signals were transmitted. The signals received by Curly from Waypoints 1 to 10 are used in the analysis. The signals at Waypoints 11 to 14 have low SNR due to large distances between source and receiver. The distance between the ship and the buoys were determined using data from GPS units mounted on the ship and in the buoys. Measurement of ocean temperature was made using XBT during the course of the experiment. The sound speed profile in the water column was obtained using the temperature profile and a constant salinity of 33.25 ppt.

B. *Formulation of inverse problem*

In shallow water wave guide acoustic propagation is best described in terms of the normal modes of propagation. Each of these modes travel along the wave guide at speeds which are dependent on the acoustic properties of the wave guide. In the experimental set up a source transmits broadband signals and the signals collected by thereceiver systems areprocessed to determine the group speeds of the modes at a set of discrete frequencies. This forms the data set used to obtain the acoustic properties of the wave guide. Typically one assumes that the water column properties are known by direct measurement and the only unknowns to be estimated are the acoustic characteristics of the sediment layers.. The approach for estimating the sediment acoustic properties from dispersion relationship, i.e. the variation of the group speed of each mode as a function of frequency, has been detailed in [2, 3]. This procedure is a linearized solution which is based on perturbation theory. Consider a range-independent ocean model whose compressional wave speed and density are represented by $c_b(z)$ and $\rho_b(z)$, respectively. For this model $k_n(\omega)$ and $\phi_n(z, \omega)$ are the eigenvalue and mode function of the n th mode, respectively, that satisfy the depth-dependent Helmholtz equation and boundary conditions associated with the waveguide model. In these expressions z refers to the depth and ω the frequency of the acoustic source. Next, perturb the compressional wave speed by a small quantity $\Delta c(z)$. This will result in a change in the group speed of the propagating modes. The relationship between the group speeds of the n th mode due to a perturbation of the compressional wave speed is given by [3]

$$\frac{1}{\hat{v}_n(\omega)} - \frac{1}{v_n(\omega)} = \frac{\partial}{\partial \omega} \int_0^\infty \frac{-1}{k_n(\omega)} \frac{\omega^2 \Delta c(z)}{c_b^3(z) \rho_b(z)} |\phi_n(z, \omega)|^2 dz. \quad (1)$$

In the above equation, v_n and $\hat{v}_n$ represent the group speeds of mode n for the unperturbed and the perturbed ocean models, respectively. By modeling the sediment as a discrete set of layers (1) can be re-written as a matrix equation of the form $\mathbf{Gm} = \mathbf{d}$ where $\mathbf{m}$ represents the corrections to the compressional wave speed values of the sediment layers, $\mathbf{d}$ the data which are the quantity on the left hand side of (1) and $\mathbf{G}$ are obtained by converting the integral in (1) to a sum. This matrix equation is ill posed and special care should be taken to solve it. A means of regularization of the solution is required to obtain meaningful solutions to the matrix equation. Several approaches to regularization such as Tikhonov method [4] and its extension Qualitative Regularization [5] have been proposed. It is shown in [6] that the formulation in (1) derived for range

independent environment can be extended to range-dependent environment but it requires a multiplicity of source/receiver combinations to solve the problem.

C. Estimation of group speed of modes

The group speeds as a function of mode number and frequency can be obtained from a knowledge of the mode eigenvalues and mode functions [7]. This assumes that the environment is fully known. In a field experiment, the group speed as a function of frequency and mode is obtained by performing short time Fourier transform (STFT) of the received signal. Such a transform provides the time for the modes to travel from source to receiver from which the mode group speeds are obtained. If the distance between the source and receiver is large, the modes are fully resolved. When the modes are not well resolved, a high-resolution method must be used to resolve the modes. The high resolution method proposed in [8, 9] involves applying warping operator to the received signal. In the analysis of the data acquired by Curly, we adopted the warping method to estimate the mode travel times and from it the group speeds of the modes knowing the distance between the source and receiver.

WORK COMPLETED

A. Analysis of data

For the purpose of analysis the region between the ships locations and the locations of the buoy (Curly) is divided in to five range independent regions. These regions are shown in Fig.1. The compressional wave speed in each of this region is estimated. We adopt the method outlined in [6] for determining the properties in a range dependent case. We use the locations of the ship and the buoy as obtained from the GPS data, to determine the path length along the paths from the source to the receiver in the different region. For estimating the properties in Regions I and II we use data from Waypoints 1, 3, and 4. For estimating properties in Region III, data for transmissions from Waypoints 5, 6, and 7 are used. For estimating the properties of Region IV and V we use data from Waypoints 8, 9, and 10.

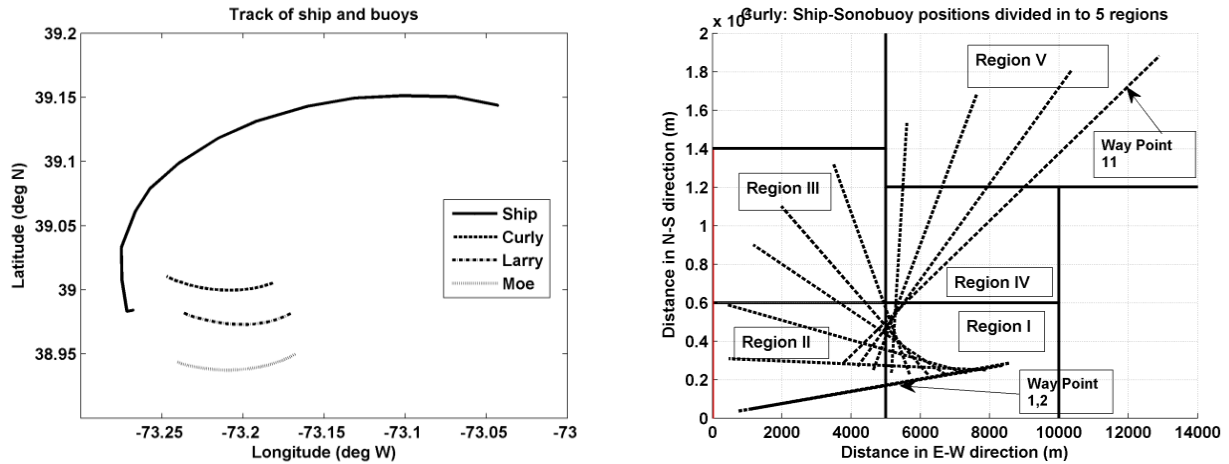


Fig 1: Left panel shows the track of ship and the sonobuoys during the experiment. The right panel shows the different source receiver paths and the range independent regions for inversion.

The data collected at the buoy Curly for 21 consecutive transmissions from each way points are summed up in order to improve the signal to noise ratio. The signal acquired by the buoy is deconvolved to get the impulse response. The warping method is then applied to the deconvolved signal and the mode travel times for the modes are obtained. This is used as data in the inverse for estimating the bottom compressional wave speed. In obtaining the bottom model, the density in the sediment layers and in the terminating half space were assumed to be 1.6 gm/cc. The attenuation in the layers were neglected. Further the compressional wave speed in the terminating half space was set at 1850 m/s. The unknowns to be estimated by the inverse are the compressional wave speeds in the layers. Qualitative regularization was adopted to solve the inverse problem. The compressional wave speed in the sediment were set to have discontinuities at specified depths.

Data used in the inversion were the mode travel times at frequencies 50 Hz to 110 Hz in 10 Hz steps. The data were restricted to travel time data for Mode 1 to Mode 4. When the distances between source and receivers were large data for Modes 1 to 3 only were available. Further, data for all the modes at all the frequencies were not usable due large errors in their values. Data from Modes 3 and 4 were restricted to values for frequencies 80 Hz and above. In the case of Mode 2 data only for frequencies at 60 Hz and above were used in some cases. Figure 2 shows the compressional wave speed in the sediment layers.

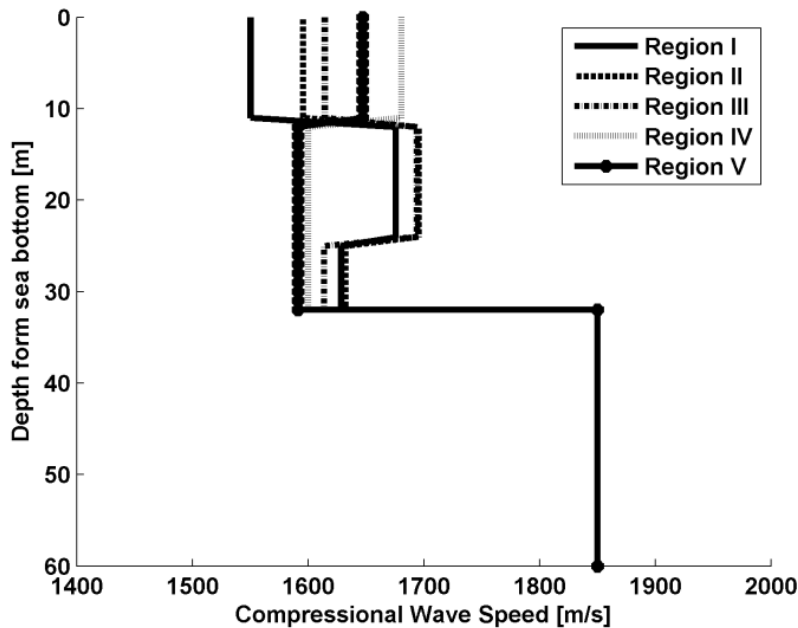


Fig 2: The compressional wave speed profiles for the five regions are shown. In the case of Regions I,II and III, the bottom compressional wave speed profile was modelled to have discontinuities at depths of 10 m and 24 m. In the case of Regions IV and V discontinuities at depth of 10 m was imposed.

B. Discussion of results

1. Comparison of mode dispersion from experiment with that predicted by the model.

Figure 3 (left panel) shows the agreement between the mode travel time obtained from data with the mode travel time from model in the case of transmissions from Waypoints 4. The inverse procedure

minimizes the difference $dt_{n,\omega} = \frac{R}{v_{n,\omega}} - \sum_{m=1}^M \frac{r_m}{\hat{v}_{n,\omega}(m)}$. The plots however have been normalised by

dividing both sides by R so that what is plotted are $\frac{1}{v_{n,\omega}}$ against $\sum_{m=1}^M \frac{r_m/R}{\hat{v}_{n,\omega}(m)}$. The close agreement between these two quantities is seen in the figure. This is to be expected because the inverse procedure minimizes the difference between these two quantities. Similar agreement is seen in all cases.

Figure 3 (right panel) shows the spectrogram of the signals at way points 1, 5, and 8 with the mode dispersion as predicted by the models obtained by the inverse. The predicted mode dispersion data are obtained based on the bottom models obtained from inversion. The figures show good agreement between the experimentally determined spectrogram and the dispersion curves from model predictions.

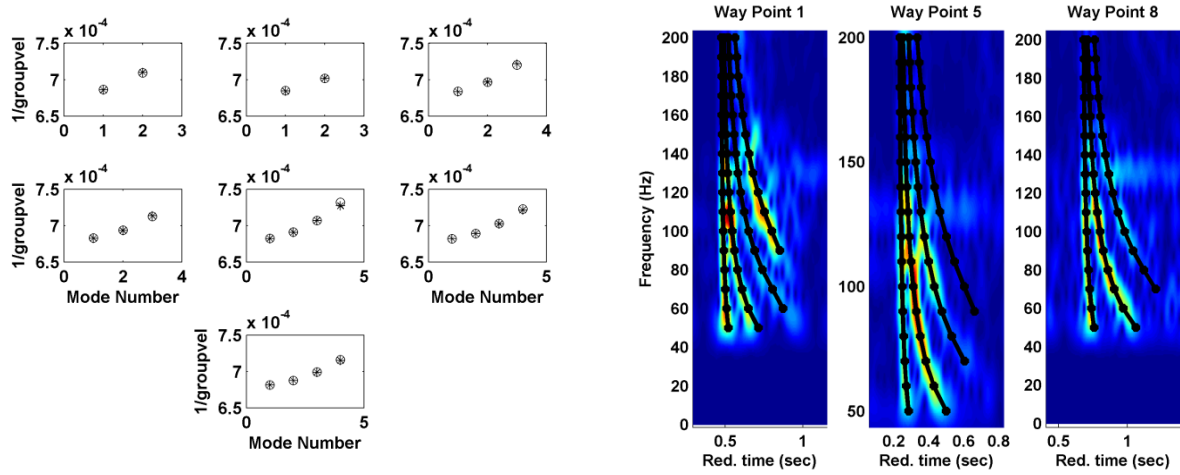


Fig 3: The left panel shows the agreement between the measured travel time data with the travel time predicted by the model. The circles are the measured values and the star are the values predicted by the model. The seven plots refers to data at the seven frequencies 50 Hz to 110 Hz used in inversion. As seen from the figure, Mode 3 data were used only for frequencies 70 Hz and above. Mode 4 data were used only for frequencies 90 Hz and above. The right panel shows the agreement between the spectrogram from measured data with the dispersion curve predicted by the models for three cases i.e way points 1, 5, and 8.

2. Comparison with other Geo-acoustic models determined during the narrow band experiment.

The broad band data analyzed here were obtained during one part of MOMAXV. The other part consisted of a narrowband experiment in which CW tones at a set of frequencies were broadcast from a moving source. These signals were acquired by freely drifting buoys. The details of the experiment are explained in [1]. During the narrow band experiment, the ship's tracks and the location of the buoys were in the general area covered by transmissions from Waypoints 3 and 4. For the narrow band

experiment, modal eigenvalues were used as input to the inversion scheme. The modal eigenvalues for Modes 1 to 3 at 50 Hz, Modes 1 to 5 at 75 Hz, Modes 1 to 7 at 125 Hz and Modes 1 to 9 at 175 Hz were used to estimate the sediment compressional wave speed. The bottom models obtained from narrow band data and the broad band data are compared in Table 1. The values of the compressional wave speeds in layers 1 and 2 are in general agreement. The value in layer 3 has a large difference. This is likely to be due to the differences in areas covered by the data in the broad band and narrow band experiments and the modal information used in inversion.

Table 1: Bottom models from narrow band and broad band experiments

Experiment	Layer 1	Layer 2	Layer 3
NB/Shemp/SB810	1568 (m/s)	1705 (m/s)	1527 (m/s)
BB/Reg I	1550(m/s)	1675 (m/s)	1628 (m/s)
BB/RegII	1595 (m/s)	1695(m/s)	1632(m/s)

We now try to predict the pressure field obtained in the narrow band experiment using the bottom model from the broad band experiment. In computing the pressure field all other parameters from the narrow band experiment such as the water column sound speed profile, the range dependent bottom depths, the source and receiver depths were used. The only difference was the parameters of the bottom. The calculations were made at four frequencies (i.e 50 Hz, 75 Hz, 125 Hz and 175 Hz). These are plotted against the field measured during the experiment. Figure 4 (left panel) shows the measured field and the field computed with the bottom model from the broad band data. Fairly good agreement between the measured field and the predicted field is seen. The wave number of the propagating modes as determined from the predicted data is slightly different from the ones obtained from the measured field. In the case of 50 Hz, this causes differences in the interference pattern and this difference is pronounced as the range increases. Even in the case of higher frequencies there are differences in the wave numbers of the modes but since there are many modes the impact of these differences in the pressure field, which is the result of the interference pattern created by these modes, are not evident. Another factor to be considered is that at higher frequencies the values of the compressional wave speed in the deeper layers are not important.

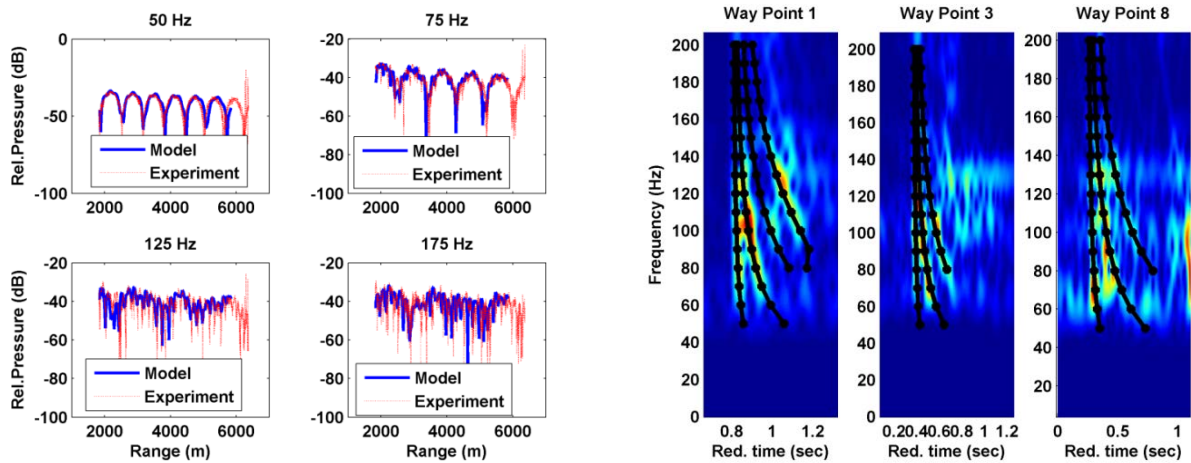


Fig. 4. (Left panel) The agreement between the measured field and the field predicted by the bottom model obtained by the inversion of the mode dispersion data are shown. (Right panel) Spectrogram of data collected by Larry for transmissions from way points 1, 3, and 8. The mode dispersion curves based on bottom model from Curly data are overlaid.

3. Comparison with data collected by other buoys

As indicated earlier, three freely drifting buoys (Curly, Larry, and Moe) were deployed before the start of the broad band experiment. In the analysis presented in earlier sections we used data collected by Curly and obtained a bottom model. We now examine if the bottom model obtained with Curly data can predict the dispersion based on data collected by Larry. The spectrogram of data collected by Larry for transmissions from way point 1, 3, and 8 are shown in the right panel of Fig. 4. Overlaid on the spectrogram are the dispersion data computed using bottom model from Curly data. Good agreement between the two is seen.

4. Comparison with other bottom models

The New Jersey shelf sediment structure is characterized by prominent reflector 'R' that is covered by sediments of varying thicknesses. These in some areas are classified as a sand layer or diffuse layer, which is followed by a layered unit. In some areas, the 'R' reflector is covered only by the layered unit. A more complete description of the sediment structure is in [1]. The New Jersey shelf area where MOMAXV was conducted has been the site of several other acoustic experiments. Inversion results from these experiments further characterize the sediment by providing an estimate of sound speed in each layer. These sound speed data are summarized in [1] and part of it is reproduced here in Table 2. Overall, there is good agreement in the sound speeds obtained by the various measurements and inversion techniques for each sediment unit as summarized in Table 2. Differences present in the estimated values may be attributed to spatial variability within each unit, the parameterization of the inversion technique, as well as the frequency band used in obtaining the results. Despite some small inconsistencies, the trends in the data are evident. For example, the layered unit, which is bounded by the diffuse layer on top and the reflector at the bottom, consistently has a lower sound speed than the surrounding layers. The sediment sound speed values estimated using the MOMAXV broad band data are shown in the last five rows. In the case of Regions I and II, the values in the deep low speed layer is much higher than the values from the narrow band experiment. This is because the inversion with broad band data was restricted to values from Modes 1 to 4, and hence was not able to estimate the values in the deep layer correctly. It is seen that in case of Regions IV and V there are no values for layer below the reflector. This is because the inverse procedure was unable to estimate values for depths greater than 24 m as data from Modes 1 to 3 only were used. The inversion results for depths greater than 24 meters merged with the initial starting value for the compressional wave speed for this layer.

Table 2: Summary of previous and current results (All values in m/s)

Reference	Sand layer	Diffuse layer	Layered unit	Below 'R' reflector	Deep low speed layer
Ballard et.al [11]		1670+/-12	1580+/-19	1725+/-15	
Rajan et.al [6]		1660-1680	1510-1650	1650-1850	
Jiang et.al [12]		1636*+/-15	1572*+/-15	1740*+/-40	
Knobles et.al[13,14]	1650 -1700		1580-1595	1720	
Narrow band exp [1]			1568	1705	1527
Broad band exp. Reg I			1550	1675	1628
Reg II			1595	1695	1632
Reg III			1614	1693	1613
Reg IV	1680		1600		
Reg V	1647		1591		

CURRENT WORK

The aim of this study is to investigate the feasibility of using a fixed broad band source and a set of freely drifting buoys to estimate the sediment properties in the area covered by the source and the buoys. The data analyzed in this report were obtained with a free floating buoy and a source which was moved to a set of fixed locations. The data were used to obtain estimates of compressional wave speed in five different regions. It was shown that the bottom models obtained are consistent with sediment models for the area obtained in other experiments. One of the draw backs of the warping method for extraction of the mode dispersion data is its inability to determine the mode dispersion at frequencies below the Airy phase for that mode. A scheme has been proposed [10] that will enable extraction of the complete mode dispersion data. The scheme uses a tiling in the time-frequency plane which accounts for dispersion. An attempt was made to implement this method but it failed to extract information at frequencies below the Airy phase. A comprehensive investigation is needed to find methods for extracting mode travel time information at frequencies below the Airy phase.

IMPACT/APPLICATIONS

The data collected during this experiment will enable validation of the proposed method for estimating range-dependent sediment compressional wave speed from modal dispersion data. Using a distributed set of receivers and a broadband source it will be possible to estimate the compressional wave speed profiles over a wide area. This will therefore be a useful tool for estimating the sediment acoustic properties from data collected during routine naval operations.

RELATED PROJECTS

The estimation of sediment properties in a shallow water environment is an active area of research. The new procedures that are likely to come out of this work will therefore be of great benefit.

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