

## **Dispersion of Sound in Marine Sediments**

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### **LONG-TERM GOALS**

A critical knowledge gap in our understanding of the interaction of sound with the ocean bottom is the frequency dependence of sound speed and attenuation in marine sediments. The long term goals of this research project are related to the investigation of dispersion of sound speed and attenuation at low frequencies ( $< 2$  kHz) in different types of marine sediments. The research involves development of effective experimental methods and inversion techniques to enable estimation of geoacoustic model parameters and their uncertainties over a broad frequency range from tens of Hz to several kHz. The wider context of this research is to achieve improved sonar system performance through greater understanding of the physics of the interaction of sound with the ocean bottom.

### **OBJECTIVES**

The research focus is on inverting modal dispersion relationships to extract geoacoustic model parameters. This approach is well known and has been used to extract information about the ocean bottom from broadband signals measured at long ranges (e.g. several tens of kms) at which the modes are well separated in time. The overall objective here is to investigate the use of time warping as a means to resolve modes at much shorter ranges. Time warping involves transforming the initial time-frequency domain to a new domain in which the modal dispersion relationships are single tones. Previous work indicated that the time-frequency information was robust to imprecise knowledge of the experimental geometry, and inversion of the modal dispersion provided good estimates of the sediment sound speed (Bonnell and Chapman, 2011; Bonnell et al., 2013). The primary objective of this work is to investigate the approach to use the information in the extracted mode amplitudes to invert for sound attenuation marine sediment.

### **APPROACH**

Previous work carried out on the use of modal amplitude information for estimating sound attenuation in the sediments suggested that the extracted modes after warping were contaminated by mode interference. Two sources of mode interference were studied. The first was due to bubble pulses of the light bulb implosion signal. The bubble pulses are delayed signals that are transformed into nonlinear responses at later times in the warped domain, causing interference with higher order modes. The second was intrinsic interference from frequencies lower than the Airy frequency of each mode.

Contributions from this component of higher order modes can impact the spectra of lower order modes. The first problem was addressed by deconvolving the bubble pulses using a light bulb waveform recorded at the source. A simulation study was carried out to investigate the intrinsic modal interference.

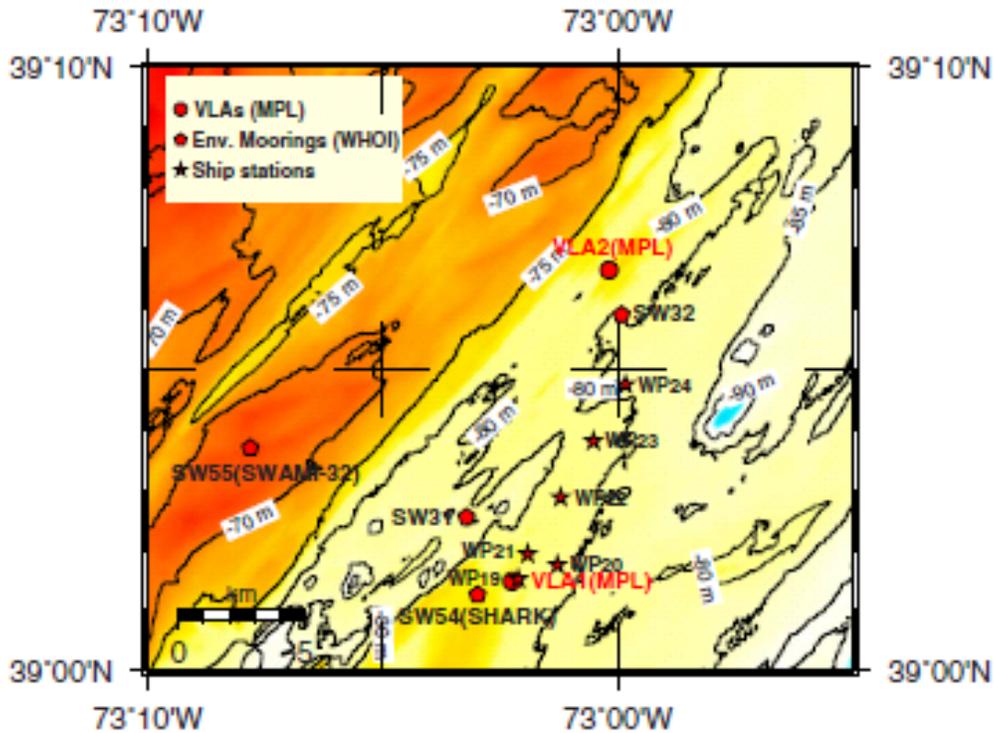
Estimation of sound attenuation in marine sediments from modal amplitudes requires knowledge of the full geoacoustic model and the experimental geometry. A new sequential inversion was designed to estimate model parameters in stages. Each stage of the inversion uses specific features of the signal to invert specific model parameters that are highly sensitive to the features. Subsequent stages use results for highly sensitive model parameters from previous stages. The method is a general Bayesian approach that enables the use of simple grid searches to evaluate the *a posteriori* probability densities in the final stages. In this work the method was applied to data from the SW06 experiment, making use of knowledge of the geoacoustic model from previous work to simplify the method. The geoacoustic model was a single sediment layer over a half space. The interface at the half space represents the R-reflector, a pervasive sub-bottom feature over the region. Since the signal strength of the light bulb sources is relatively low, it is not expected that there is high sensitivity to the model parameters below the interface.

The first stage of the inversion uses the time-frequency information of the extracted modes to invert the sediment sound speed and layer thickness. Previous work has shown that this feature is robust to imprecise knowledge of the experimental geometry and modal interference. In subsequent stages, precise knowledge of the experimental geometry is required to invert sound attenuation in the sediment. The second stage uses the mode depth function, which is sensitive to the receiver depths, to invert for receiver depth and water depth at the array. The final stage uses the extracted mode spectra to invert for source depth and the attenuation. Performance of the inversion was assessed by comparing estimated parameter values with ground truth information of the experimental geometry, and with estimated values from previous work.

## **WORK COMPLETED**

Simulations were carried out to test the impact of mode interference in time warping. The study compared the mode spectra for extracted modes with simulated modal spectra for single mode signals. The extracted modes are first filtered in the warped domain using a mask filter, and then inverse transformed to the original time-frequency domain to obtain the spectra. The simulated mode signals were generated over the data frequency band using the normal mode program Kraken. A range independent propagation environment was assumed.

The sequential inversion method was applied to broadband data from light bulb sound sources deployed in the SW06 experiment. The signal ranges were ~5 and ~7 km, and the data were received on the MPL vertical array moored at the MORAY site (Figure 1). G40 light bulbs with a relatively flat frequency band from 50-200 Hz were used in the inversion.

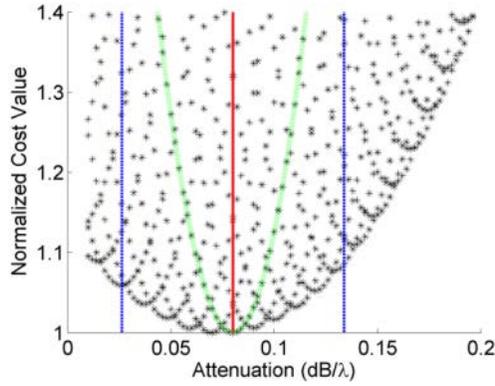


*Figure 1. The SW06 experimental site. The light bulb deployment sites are near positions WP23 and WP24.*

## RESULTS

Deconvolution of the bubble pulses improved the frequency response of the extracted modes, particularly at low frequencies, and enabled the use of a portion of the frequency band from 50-180 Hz for the inversions.

Estimated values of the sound speed profile from the first stage (time-frequency) inversion were consistent with values obtained by other researchers using other SW06 experimental data at the same site. Confidence in the inversion was also provided by the estimates of water depth at the array and the receiver depths. The results for the attenuation are shown in figure 2. In this stage of the inversion only two parameters were estimated, enabling a simple grid search; the values of the other parameters were assumed known. Table 1 lists the inversion results from the last two stages of the inversion, in comparison with known values from ground truth data in the experiment.  $D_{re}$  is the receiver depth,  $z_s$  is the source depth and  $\alpha$  is the attenuation.



**Figure 2. Sensitivity analysis of the mode amplitude spectrum inversion for the 5 km source. The green curves denote the normalized cost values with the fittest source depth a priori.**

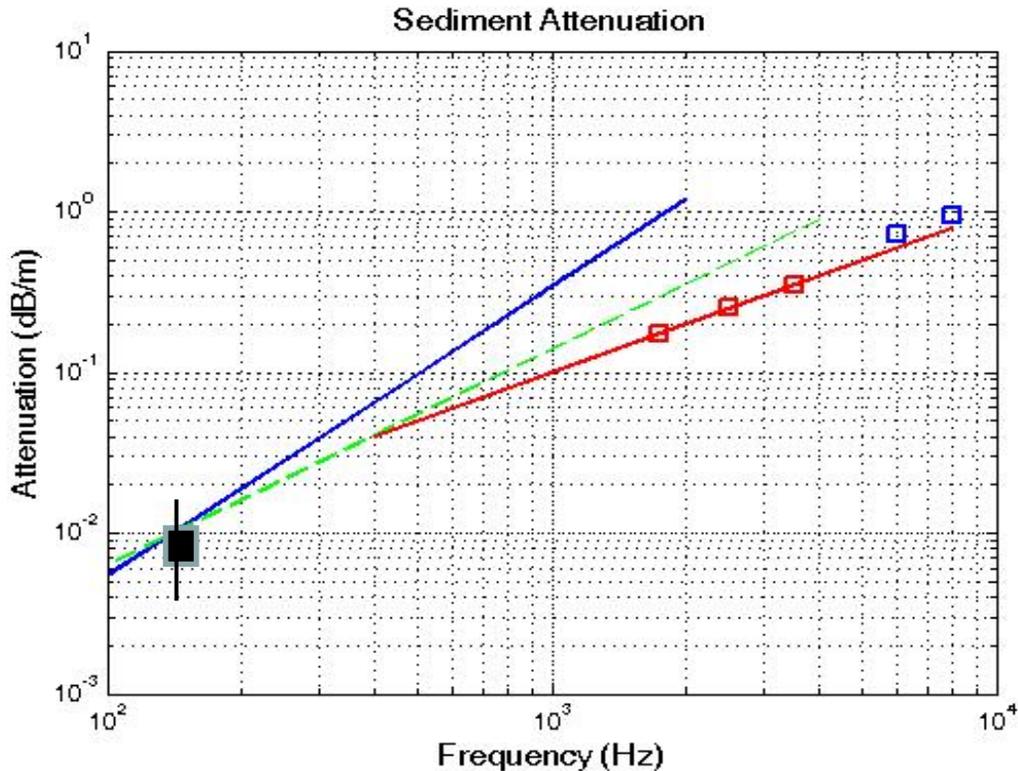
**Table 1 Summary of inversion results of stages 2 and 3**

Parameter	Unit	Search bounds	Source	Estimated value	Reference value
$D_{re}$	m	[74 84]	G40, 5 km	78	77.5
			G40, 7 km	77.6	
$z_s$	m	[16 22]	G40, 5 km	21	<21.6
			G40, 7 km	19.3	
$\alpha$	dB / $\lambda$	[0.01 0.2]	G40, 5 km	0.08	0.078-0.13
			G40, 7 km	0.076	

The estimate for low frequency sound attenuation is indicated by the black square in Figure 3. Also shown in the figure are results from different inversions covering a frequency band from ~100 Hz to 6 kHz for comparison. The broken green line is from the low frequency (100-700 Hz) matched field inversion of Jiang and Chapman (2009); the blue squares are from the spectral ratio inversions of Turgut (2008); the red squares are the travel time inversions of Jiang and Chapman (2010) and the black line is the prediction of Carey for the New Jersey shelf region (Dediu et al, 2007). The results for the low frequency attenuation are consistent with the low values in the vicinity of this site from the inversions of higher frequency data. At higher frequencies, the frequency dependence is linear. The data suggest a deviation from linear variation with frequency at some point below about 2 kHz. Work is continuing to use other sound sources, including light bulbs, to determine the nature of the frequency response between 200-1000 Hz.

### IMPACT/APPLICATIONS

Sequential inversion of mode amplitude and phase obtained by time-warping of broadband data is a promising technique for estimating sound attenuation in marine sediments at low frequencies. The method is insensitive to exact knowledge of the experimental geometry and sound speed in the water, and can provide high resolution modal data at relatively short ranges.



**Figure 3.** *Estimated attenuation from (1) modal amplitude spectra (black square); spectral ratios (blue squares); travel time sub-bottom signal (red squares); matched field inversion (green line). The blue line is the predicted attenuation from Carey.*

## RELATED PROJECTS

The knowledge gained in this work will identify gaps in our understanding that can be addressed in designing the next phase of experiments. The research is connected with research projects of the following: W. S. Hodgkiss and P. Gerstoft (MPL, SCRIPPS); D. Knobles (ARL:UT); G.V. Frisk (Florida Atlantic); P. Dahl and D.J. Tang (APL UW); J. Miller and Gopu Potty (University of Rhode Island), J. Goff (U of Texas at Austin) and J. Lynch (WHOI). The overall goal of this group is to characterize the geoacoustic environment and understand mechanisms of the interaction of sound with the ocean bottom.

Links have also been made with other researchers supported by ONRG. Dr Laurent Guillon spent a 6-month sabbatical at UVic to collaborate in development of his image method for geoacoustic inversion. A paper is being written to summarize the research carried out over the visit. Data from SW06 was shared with Dr Michael Taroudakis in collaborative work on a new inversion technique. The broadband light bulb data were supplied to him for use a sound source in a test of the inversion technique with experimental data. A paper to summarize the work was submitted to JASA EL.

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