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As part of the SAX04 experiment, sound speed and attenuation were measured in the seabed off of Ft. Walton Beach, Florida, USA, at frequencies from 1 to 400 kHz. For the lowest frequencies, from 1 to 20 kHz, signals from two acoustic sources were recorded on an array of hydrophones emplaced at depths of up to 1 m below the seafloor within a 4 m by 4 m area. At frequencies from 15 to 200 kHz, sound speed and attenuation data was obtained using the In Situ Sediment Acoustic Measurement System (ISSAMS), a linear array of four piezoelectric probes that were inserted into the seabed to a depth of 0.3 m. Sound speed measurements were also made at 60, 100, 200, and 400 kHz on diver-collected cores using four separate pairs of ultrasonic transducers. Sound speed data from the core and ISSAMS measurements demonstrates an essentially uniform

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FREQUENCY DEPENDENT SOUND SPEED AND ATTENUATION MEASURENTS IN SEAFLOOR SANDS FROM 1 TO 400 KHZ

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As part of the SAX04 experiment, sound speed and attenuation were measured in the seabed off of Ft. Walton Beach, Florida, USA, at frequencies from 1 to 400 kHz. For the lowest frequencies, from 1 to 20 kHz, signals from two acoustic sources were recorded on an array of hydrophones emplaced at depths of up to 1 m below the seafloor within a 4 m by 4 m area. At frequencies from 15 to 200 kHz, sound speed and attenuation data was obtained using the In Situ Sediment Acoustic Measurement System (ISSAMS), a linear array of four piezoelectric probes that were inserted into the seabed to a depth of 0.3 m. Sound speed measurements were also made at 60, 100, 200, and 400 kHz on diver-collected cores using four separate pairs of ultrasonic transducers. Sound speed data from the core and ISSAMS measurements demonstrates an essentially uniform sound speed near 1780 m/sec. Preliminary analysis of the sound speeds from the low frequency array data demonstrate an anomalous increase in sound speed values with decreasing frequency when sources were emplaced below the seafloor, attributable to the influence of multi-path arrivals. Data from source locations at the seafloor demonstrate a decrease in sound speed with decreasing frequency, consistent with the trend predicted by the Biot model, but with large uncertainties. Attenuation values from seafloor source positions follow a square-root frequency dependence below 20 kHz, similar to the Biot predicted trend, while the core and ISSAMS data demonstrate a near linear trend at higher frequencies. A fit of the Buckingham model to the sound speed and attenuation data results in a good fit to the higher frequency attenuation data, but underpredicts the attenuation observed at frequencies below 20 kHz. Future work, including full waveform inversion of the low frequency data and detailed error analysis, should reduce the uncertainty in the sound speed analysis at low frequencies and determine the ability of the measurements to discriminate between the models.

1 Introduction

Frequency-dependent variation in the sound speed and attenuation in seafloor sediments produces consequent frequency-dependant variation in the magnitude of the wave energy reflecting from and transmitted into the seafloor at a given angle of incidence. An understanding of this frequency dependence is important for reliable detection and imaging of sub-seafloor features and for prediction of long-range sonar losses resulting from acoustic interactions with the seafloor. While sound speed and attenuation measurements at high frequency are relatively straight forward, the

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measurement of their frequency dependence is more difficult due to the limited frequency band of individual measurement systems and to the wide range of scales required for measurements over a broad frequency band. Nevertheless, the extrapolation of a single frequency measurement to a broader range of frequencies can be performed if reliable empirical or theoretical relationships have been established to describe the frequency dependences over the desired frequency range. The objective of this study was to measure the sound speed dispersion and frequency-dependent attenuation in a homogenous seafloor sand over a wide range of frequencies, and to assess the ability of Biot-Stoll and Buckingham propagation models to predict the observed frequency dependences.

Biot's model [1,2] predicts the frequency dependence of the sound speed and attenuation due to relative motion between a viscous pore fluid and a porous framework caused by the deformation and displacement occurring with the passage of small-strain elastic waves. As pore fluid movement is central to this model, its inputs include a number of pore space descriptors, including the porosity, permeability, pore size, and tortuosity, as well as the pore-fluid density, bulk modulus, and viscosity, the sediment-grain bulk modulus and density, and the elastic moduli of the dry grain framework. This model predicts significant sound speed dispersion and a characteristic double power law dependence of the attenuation on the frequency, which is proportional to the square of the frequency at low frequency and to the square root of the frequency at high frequency. The Buckingham model [3,4] describes the frequency dependence resulting from stochastic stick-slip sliding at grain contacts in a grain framework with no global elastic stiffness. This model requires knowledge of the grain and pore fluid properties, as well as inputs that describe the frictional sliding at the grain contacts. These parameters cannot be determined from an independent characterization of the sediment, but can be derived from calibration based on measurement of the wave speed and attenuation at a single frequency, or from a fit of the model to multi-frequency measurements. The Buckingham model predicts a weak, approximately logarithmic frequency dependence for the sound speed, and a nearly linear frequency dependence for the attenuation.

Buckingham and Richardson [5] and Williams et al. [6] compared sound speed dispersion and frequency-dependent attenuation, measured with a variety of techniques during the Sediment Acoustics eXperiment of 1999 (SAX99) off of Fort Walton Beach, Florida, USA, to the Biot-Stoll and Buckingham model predictions over a frequency range from 0.4 to 400 kHz. Buckingham and Richardson [5], using a subset of the data over a frequency range from 25 to 100 kHz, found that while the sound speed dispersion predicted by both the Biot and Buckingham models fit the measured dispersion, the attenuation data was more consistent with the Buckingham model. Williams et al. [6], with the larger dataset and with inputs from detailed characterization of the seafloor, found that below 50 or 100 kHz the Biot model successfully describes the trend of the observed attenuation and sound speed. Above this frequency, the measured attenuation deviates from that predicted by the Biot model, but follows a trend attributable either to scattering or to the Buckingham sliding mechanisms.

This study, conducted as one component of the SAX04 experiment, involved measuring the sound speed and attenuation at frequencies from 0.6 kHz to 400 kHz in the relatively homogenous sands in the first meter below the seafloor at a site about 1000 m off of Fort Walton Beach, Florida, USA. This frequency range spans the high frequency, sound speed maximum of the Biot-Stoll model and most of the predicted transition to the low frequency minimum. A prime focus of the experiment was to make accurate measurements at lower frequencies (< 20 kHz), as most of the Biot-predicted dispersion occurs at these low frequencies and as there were large measurement uncertainties at these low frequencies in previous studies [6].

2 Experimental Measurement Systems

To cover the frequency range of interest, sound speed and attenuation were measured with three separate measurement systems. These included a diver-emplaced hydrophone and geophone array for measurements at frequencies below 20 kHz, a four probed piezoelectric array from 15 to 200 kHz, and a laboratory core measurement system from 60 to 400 kHz. Here each of these systems is described in detail.

2.1 Buried Hydrophone and Geophone Array: 0.6 to 20 kHz

The low frequency recording system consists of a sub-seafloor array of 35 hydrophones and 5 three-component accelerometers which was used to record signals from two acoustic sources positioned on or below the seabed near the array. The hydrophones each consist of a piezoelectric element, attached to a small pre-amp and potted in polyurethane. Each three-component accelerometer consists of three high sensitivity (1 V/g), uniaxial piezoelectric accelerometers, mounted orthogonally in an aluminum pressure case. Divers implanted the receivers along three azimuths within a 4 m by 4 m area at depths of up to 1 m (Figure 1a) using a positioning template consisting of an aluminum frame with guide tubes mounted at each of the receiver locations (Figure 1b). The water jet tools used to insert the sensors into the seabed required re-engineering in the field, resulting in inaccuracies of several cm in the positions of the receivers. Each of the receivers was connected to a seafloor data acquisition unit, which provided signal conditioning (amplification and analog filtering) to each receiver output and power to each receiver. The outputs from each receiver were recorded eight at a time at a sample rate of 102.4 kHz, and stored on a computer. The acquisition system was attached to the ship with a cable which provided power to the system and allowed fiber-optic communication with the acquisition computer.

The sources, a Helmholtz generator, driven at frequencies from 0.6 to 6 kHz, and an ITC 3013 hemispherical transducer, driven at 6 to 20 kHz, were each positioned at points along each of the main azimuths of the receiver array at offsets from 3 to 18 m from the center of the array (Figure 1a). At most source locations, the sources were water jetted to a depth of 50 cm below the seafloor, although at locations nearest to the array they were also placed at the seafloor and at depths of approximately 1 m. Source signals, consisting of 10 cycle tone bursts at each frequency, were generated with a D-to-A card at a 250 kHz update rate, passed through a 50 kHz low-pass analog filter, amplified with an amplifier, and sent down a 120 m long cable to the source. The signals recorded on each receiver were stacked at least 10 times.

Figure 2 shows representative signals from each source recorded on the hydrophone (Fig. 2a) and accelerometer (Fig. 2b) located at the center of the array. Though the accelerometers are significantly more sensitive than the hydrophones, they are much too ringy to provide usable signals. Nevertheless, high quality signals are recorded with each of the hydrophones at all but the highest frequencies (above 15 kHz), where electrical system noise starts to be significant relative to the strength of the signal at far offsets.

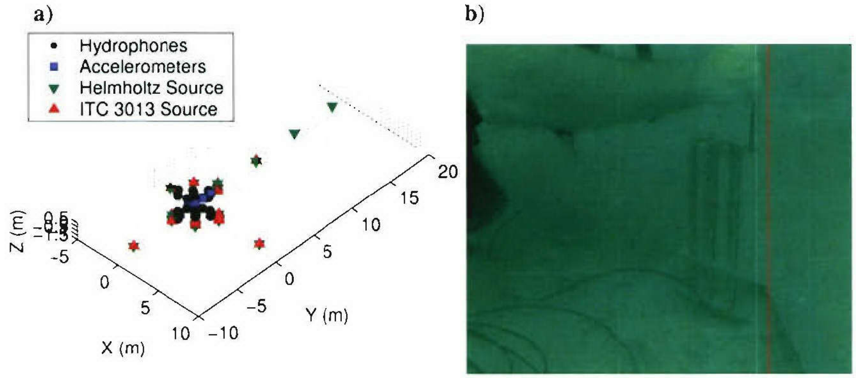


Fig. 1: a) Map of source and receiver locations for the low frequency, buried array system, and b) photograph showing a diver water jetting a hydrophone into the seafloor.

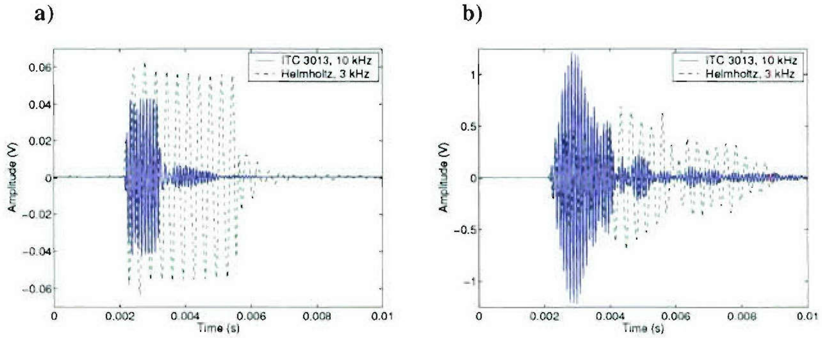
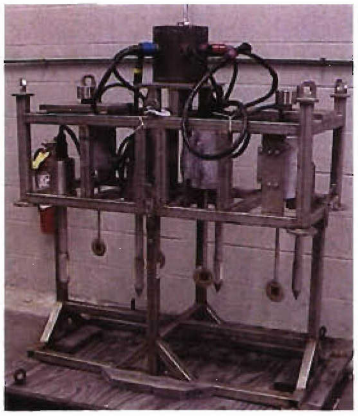


Fig. 2: Typical receiver signals recorded with the low frequency array on a) a hydrophone, and b) a vertical accelerometer channel, for a source offset of 3 m.

2.2 *ISSAMS: 25 to 200 kHz*

The In Situ Sediment Acoustic Measurement System (ISSAMS) consists of two linear, 4-probe piezoelectric arrays, mounted rigidly on a diver-emplaced frame at a spacing of 30 cm (Figure 3a). Each probe extends 30 cm below the base of the frame, and contains a piezoelectric element encased in the tip of the probe. One set of probes contains compressional elements, while the other contains shear elements. The outer probes in each array act as transmitters, while the inner probes serve as receivers. The compressional probes were driven with source signals consisting of tone bursts of between 5 and 25 cycles at individual frequencies from 15 to 200 kHz. The differential output of the receiver probes was recorded individually at a sample rate of 2.5 MHz with a high speed digital recording system. The system was deployed at three locations within approximately 100 m of the site of the low frequency buried array. A sample set of waveforms from one of these deployments is shown in Figure 3b.

a)



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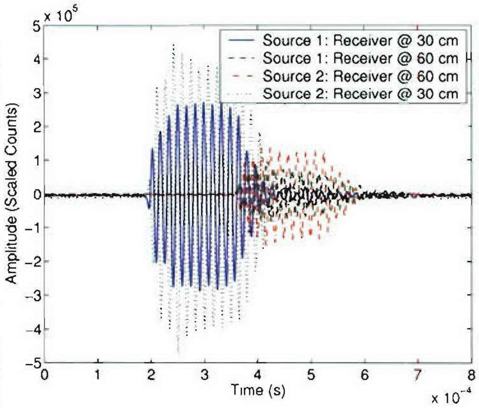
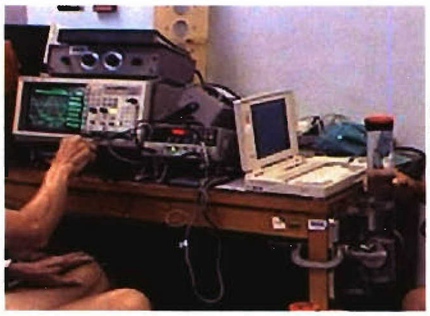


Fig. 3: a) Photograph of ISSAMS frame and probes, resting in its support stand. The acoustic probes are pointed, while the shear probes are paddle shaped. b) Typical acoustic signals collected on two receivers from the same source.

a)



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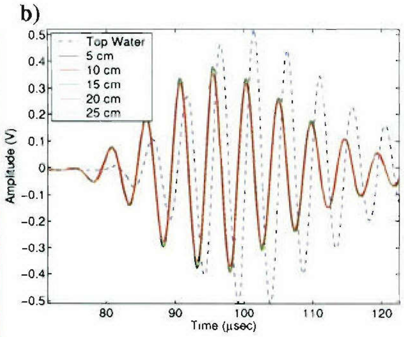

Fig. 4: a) Photograph of the core measurement system, and b) signals collected from one of the cores at 200 kHz.

2.3 *Cores: 60 to 400 kHz*

Sound speed and attenuation measurements were also made on sediments retained in 5 cores collected around the site of the buried array system using 4 individual sets of transducers with nominal resonance frequencies of 60, 100, 200, and 400 kHz. Each pair of transducers was placed on either side of the core tube, and one transducer was driven with 5 cycles at the resonance frequency. The waveform received by the other transducer was recorded with a digital oscilloscope, with a sample rate varying with the frequency of the transducers used. For each set of measurements, signals were recorded through the water in the core tube overlying the relatively undisturbed sediment, and at depths of 5, 10, 15, and 20 cm below the sediment-water interface. Figure 4 shows a photograph of the set-up and examples of waveforms collected for one of the cores at 200 kHz.

3 Data Analysis and Results

Waveforms recorded with each of the three measurement systems were processed to calculate values of the sound speed and attenuation at each measurement frequency. Core data were resampled 100 fold, windowed over the first five cycles, and cross-correlated with the windowed signal propagated through the overlying water. The sound speed was calculated from the time lag between the two signals and the inside diameter of the core (5.9 cm), assuming a water velocity of 1526 m/s (room temperature), and then corrected to in situ conditions. The attenuation was calculated as 20 times the log of the ratio of the RMS magnitudes of the windowed segments of the sediment and water signals, assuming negligible attenuation in the water. The sound speeds at the higher three measurement frequencies (100, 200, and 400 kHz) are essentially constant with frequency, varying from 1775 to 1810 m/sec (Figure 5a). At 60 kHz, the sound speeds are approximately 30 m/sec higher. We presume the higher values at this frequency result from bias in the measurement technique. The attenuation measured in the cores demonstrates an approximately linear frequency dependence at all four measurement frequencies (Figure 5b).

The ISSAMS data were filtered to a band from 25% below to 25% above the nominal frequency of the tone burst. The sound speeds were then calculated from time-delay differences between signals recorded from the two receivers, with the effective receiver-receiver spacing calculated from the time delay between signals recorded while the system was suspended in the water column. Attenuation was calculated from the ISSAMS measurements by the transposition method [7]. The sound speed results from the ISSAMS data are essentially constant with frequency above 50 kHz, generally varying between 1770 and 1790 m/sec and overlapping the higher frequency core data. Below 50 kHz the sound speeds increase anomalously, which we attribute to some sort of interference, whether due to a multi-path arrival or resonance in the support frame, that is also evident in the time delays observed during calibration. Similar behavior is evident in the attenuation results, where above 50 kHz the data follow a trend consistent with that observed in the core data, while at lower frequencies they rise anomalously.

The data from the low frequency array were deconvolved with a source wavelet derived from the signal recorded at each frequency at the hydrophone nearest to the source when the source was positioned 1 m off the south end of the array at a depth of 50 cm. Arrival times for each hydrophone were then picked from the peaks of the deconvolved traces. Sound speeds were calculated for each source location from a linear least-squares fit to the arrival time vs. distance data. Attenuations were calculated by fitting an exponential to the peak magnitudes of the deconvolved traces vs. distance from source to receiver, and correcting for spherical spreading. Only hydrophones at depths of 50 cm or more below the seafloor were used to calculate the sound speed and attenuation, as tests of the analysis procedure on simulated data demonstrated large biases in the results from the shallower hydrophones due to interference from evanescent energy. Sound speeds calculated from deeper source locations (50 cm or more below the seafloor) demonstrate a consistent increase in speed with decreasing frequency, while the attenuation data from the same source locations decrease to a minimum at 3 kHz, below which they increase with decreasing frequency (black points in Figure 5). Tests on simulated data suggest that these results may be strongly influenced by reflections at the seafloor for the buried source and receivers. Results from data where the source is positioned at the seabed and this multi-path is not present (red points in Figure 5) demonstrate sound speeds between 1730 and 1770 m/sec at frequencies at 10 to 12 kHz, decreasing to values between 1650 and 1700 m/sec below 2 kHz. Uncertainties in these values from the least-squares regressions are on the order of 10%. The attenuation data for the seabed source positions demonstrate a consistent square-root dependence with frequency. Future analyses based on full waveform matching of the signals will be necessary to remove any influence of evanescent energy and to reduce the uncertainty of the results.

a) b)

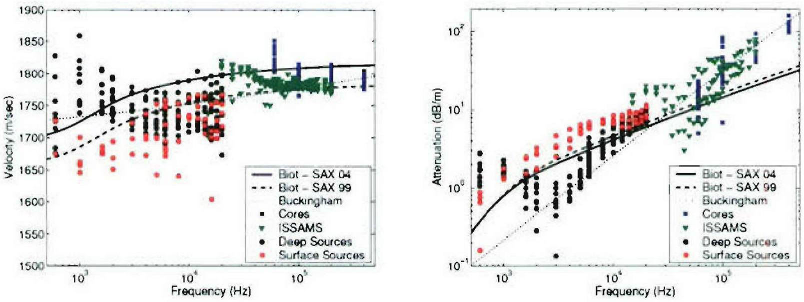

Fig. 5: Experimental results for a) sound speed and b) attenuation measurements from all three experiment components, along with theoretical predictions.

Figure 5 also shows the frequency dependent predictions of the Biot and Buckingham models. The Biot model was parameterized both with inputs from [6] based on the characterization of cores collected from the site during SAX99 (dashed line), and with updated inputs, where available, from sediment characterization from SAX04 cores (solid line). The differences in the Biot sound-speed predictions are mostly due to the lower porosity value used (0.3665), an average value from measurements on two cores from SAX04. Williams et al. [6] use a higher porosity value (0.385) chosen from within the range of measured porosity values from SAX99 to fit the model to the sound speed data. The Buckingham model was fit to the data by treating the uncharacterizable parameters as free parameters, as described in [5].

4 Discussion and Conclusions

While the sound speed values from shallow source positions demonstrate a trend similar to that predicted by the Biot model, the fit of the Buckingham model also falls within the uncertainty in the sound speed values at all frequencies. For the attenuation values, the Biot model predictions match the attenuation data at low frequencies, while other phenomena, whether scattering, local flow, or grain contact slip mechanisms, must be invoked to the account for the attenuation of the acoustic energy at higher frequencies. The uncertainties in the sound speed and attenuation values from these preliminary analyses do not permit a conclusive test of the validity of the different propagation models. We hope to decrease the uncertainty in the sound speed and attenuation values derived from these experiments by performing full waveform inversions of the low-frequency data. This approach combined with a detailed error analysis may allow a better assessment of the ability of various models to describe the acoustic propagation properties of these sands.

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