CALCULATION OF IN SITU ACOUSTIC WAVE PROPERTIES IN MARINE SEDIMENTS

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The importance of estimating compressional wave properties in saturated marine sediments is well known in geophysics and underwater acoustics. As part of the ONR sponsored Geoclutter program, in situ acoustic measurements were obtained using ISSAP (In situ Sound Speed and Attenuation Probe), a device developed and built by the Center for Coastal and Ocean Mapping (CCOM). The location of the Geoclutter field area is the mid-outer continental shelf off New Jersey. Over 30 gigabytes of seawater and surficial sediment data was collected at 99 station locations selected to represent a range of seafloor backscatter types. At each station, the ISSAP device recorded waveform data across five acoustic paths with nominal probe spacing of 20 or 30 cm. The transmit/receive probes were arranged in a square pattern and operated at a nominal frequency of 65 kHz. The recorded waveforms were processed for sound speed using two methods, cross-correlation and envelope detection, and compared. The waveforms were also processed for sediment attenuation using the filter-correlation method. Results show considerable variability in the acoustic properties at the same and nearby seafloor locations.

1 Introduction

The earliest published work involving in situ measurement of acoustic properties was performed using diver deployed probes in shallow water [1], a difficult and time-intensive task. During the late 1960’s, a deep-diving submersible [2] was used to measure the attenuation of compressional acoustic waves in deep-water, but again divers were left to deploy probes in shallow waters and only a small number of stations were measured. A complete summary of the early research is contained in [3]. Recently, in situ measurements have been obtained with sophisticated platforms capable of obtaining multiple, rapid measurements of near surface values of sediment geoaoustic and geotechnical properties [4, 5]. Current propagation models predicting the interaction of acoustic waves with the seafloor are limited by a lack of data correctly depicting the spatial variability of the seafloor. To expand present understanding of acoustic wave propagation mechanisms in marine sediments, it is imperative to obtain abundant and high-resolution measurements in their natural setting.
2 Experiment Description

As part of the ONR Geoclutter program the Center for Coastal and Ocean Mapping designed, built, and deployed ISSAP, a geoacoustic measurement system capable of measuring surficial sediment compressional wave velocity and attenuation. ISSAP was constructed of aluminum and stainless steel, weighed approximately 275 kg, had a height of 1.5 m, and a 9.4 m square footprint. It had two principal parts; an outer frame that acted as a guide for an inner frame assembly. The outer frame consisted of a protective tripod reinforced with a tapered skirt. Articulated tripod feet allowed for vertical probe insertion on slopes up to 20 degrees. Included in the inner frame assembly were a load bearing box beam structure, a 0.36 m square aluminum platform, and a guard ring slightly larger than 1 m in diameter. Mounted on the inner frame platform were two pressure housings for electronics, a color video camera and light, and a Jasco Research UWINSTRU, which measured platform heading, pitch, and roll, depth, and bottom water temperature. The transducer probes were mounted to the underside of the platform with Delrin™ precision machined collars (Figure 1) designed to minimize travel of the acoustic signal through the ISSAP frame and displacement of the probes during insertion. Multiple locations were available for probe placement. Acoustic path lengths were adjustable in 10 cm increments from 10 to 60 cm.

The ISSAP instrument used four transducer probes arranged in a square pattern giving approximate acoustic path lengths of 30 cm and 20 cm. The active elements were piezoelectric ceramic cylinders with diameter and length of 2.54 cm. Overall probe length was about 30 cm which allowed for up to 20 cm insertion into the sediment. The active zone of the transducer was located at a maximum insertion depth of 15 cm. The transducers were used to transmit and receive, and operated at a frequency of 65 kHz. Sensitivity and response between transducer pairs at different angles was approximately equal.

Five acoustic paths were used to measure compressional speed of sound and attenuation; two long paths (30 cm) and three short paths (20 cm). A 40 μs pulse was generated at a repetition rate of 30 Hz. The acoustic signal detected by the receive transducer was amplified and combined with the transmitter gate pulse to generate a composite signal (see Figure 2). The gain mode was set to LOW (0 dB) for seawater measurements and HIGH (12 dB) for most sediment measurements. The composite signal was sampled at a frequency of 2 MHz with a National Instruments PCI-6110E A/D data acquisition board. The composite sampled waveform contained all information necessary to calculate the time-of-flight of the acoustic pulse. A distilled water calibration procedure was performed to compensate for fixed system delays. For a complete description of the ISSAP instrument see Mayer et al. [6].

Acoustic measurements with ISSAP, and sediment samples from the seafloor (grab and a few slow-core), were collected at 99 station locations over an area approximately 1300 square km. At each location, the ISSAP instrument was lowered to a height ~10 m
above the seafloor. A measurement cycle (150 measurements) was obtained in seawater for calibration purposes and for use in the attenuation calculation. Using the real-time video as a guide, ISSAP was lowered and the transducers inserted in the sediment. Two sediment measurement cycles were obtained for a total of 300 acoustic measurements. ISSAP was removed from the sediment, raised to a height of ~10 m above the seafloor and a second seawater measurement cycle obtained. Due to failure of the UWINSTRU A/D board, the bottom water temperature and depth were not measured for most stations. Data obtained at 2 stations could not be processed.

3  Data Processing

3.1  Sound speed

3.1.1  Cross-Correlation

The relative time delay between two signals may be estimated from the peak of the cross-correlation of the two signals [7]. The cross-correlation function is estimated as a function of correlation lag and has its maximum at a lag equal to the time delay. First, the time-of-flight in seawater was calculated as the elapsed time between two zero-crossings of the seawater sampled waveform (see Figure 2); the zero-crossing with negative slope from the trigger and the first zero-crossing with positive slope on the received waveform. Least-squares regressions were performed to resolve the zero crossing between samples. After flight times in seawater were calculated, cross-correlation of the sediment waveform with the seawater waveform was performed to estimate the relative time delay. The cross correlation was limited to the first half cycle of each waveform to prevent a tendency (or shift) in correlation lag towards secondary multipath arrivals. The time-of-flight of the acoustic pulse in the sediment was determined as the difference of the seawater time-of-flight and the time delay estimate from the cross-correlation. Shown in Figure 2 are typical results obtained after performing the cross-correlation.

A disadvantage of the cross-correlation technique was that determination of the peak correlation (lag resolution) was limited by the sampling frequency of the received
waveforms. Estimation of the peak correlation was improved by performing a cubic least squares regression. In some sediment types, loading on the transducers produced waveforms with slow rise times. In these instances, the cross-correlation technique may underestimate the sediment sound speed. To address these problems the sound speeds were also calculated using envelope detection. This method additionally considers phase differences between the seawater and sediment waveforms.

3.1.2 Envelope Detection

This method required a filtering step to remove an artifact on the leading edge of the seawater waveforms possibly due to a high-frequency mode of the piezoelectric crystal. The seawater waveforms were low-pass filtered using a 5th-order Butterworth digital filter with a 3 dB dropoff at the cutoff frequency of 90 kHz. To compensate for the effect of the filter delay on the seawater waveforms, the sediment waveforms were also filtered using the same filter. The waveform envelopes were determined from the magnitude of the discrete analytic signal. By definition, an analytic signal is a complex signal that has the original signal in the real part and the Hilbert transform of the original signal, a 90° phase shifted version of the original signal, in the imaginary part.

The time-of-flight (in seawater and sediment) was calculated as the elapsed time between the trigger zero crossing with negative slope and the zero-crossing of (extracted from) the leading edge of the envelope. Waveform envelopes were normalized by the first detected peak and the zero crossing determined by performing a linear least square regression to all samples between 0.4 and 0.8 of the normalized amplitude. A second calibration step was needed to determine the effective acoustic path lengths using this zero crossing.

3.2 Attenuation

Attenuation in marine sediments may be estimated using either time or spectral domain methods. Spectral domain methods are difficult to use when secondary reflections of the transmitted pulse are located within the sampling window of the first arrival pulse. In this instance, short window lengths in the time domain are required to separate the secondary arrival from the first arrival, which greatly reduces the spectral resolution. To overcome the limitations of the spectral methods, a filter-correlation method was proposed by Courtney and Mayer [8]. This method showed accurate estimates of attenuation parameters could be obtained even when window lengths in the time domain were reduced to minimize the effects of secondary reflections. Additionally, the filter correlation method may be used to estimate attenuation as a function of frequency by filtering a broadband signal with bandpass filters over a range of passbands, and cross-correlating the filtered attenuated signal with a filtered reference signal.

Although a narrow band signal was used in this experiment, bandpass filtering the received waveforms aided the identification of secondary reflections. No attempt was made to estimate attenuation as a function of frequency. All waveforms were filtered using an 8th-order digital Butterworth filter with passband from 52 to 82 kHz and a 3 dB dropoff at the passband edges. The envelopes of the bandpass filtered waveforms were determined from the magnitude of the analytic waveform as described above. To account for phase differences between the seawater and sediment arrivals, it was important to perform the cross-correlation using the envelopes of the waveforms,
derived from the Hilbert transform, and not the waveforms themselves. After the waveforms were correctly aligned the sediment attenuation (in dB/m) relative to the bottom water was calculated using

$$\alpha = -20 \log_{10} \left( \frac{A_s}{A_w} \right) \cdot \frac{1}{\Delta L}$$

(1)

where $A_s$ represents the $rms$ energy in the sediment waveform, $A_w$ represents the $rms$ energy in the seawater waveform, and $\Delta L$ is the measured physical path length between the transmit and receive transducer probes. The number of samples used to calculate the $rms$ energy was determined by the length of the sediment waveform and included all samples from the leading edge of the envelope to the zero-crossing prior to the first peak of the sediment envelope (see Figure 3).

An algorithm based on the deviation between the sediment and seawater envelopes was used to help identify waveforms corrupted by early secondary reflections. The sediment envelopes were cross-correlated with the seawater envelopes and normalized by the first (arrival) peak of the envelope. The seawater envelope was shifted in time by the correlation lag and the deviation between the seawater and sediment envelopes calculated. Mean deviations were determined for all samples along the leading edge of the sediment envelope. For example, the mean deviation for the $n^{th}$ sample was determined as the average of the $n-1$, $n$, and $n+1$ sample deviations. The mean deviations were summed over the same range of samples used in the attenuation calculation. In some instances, the sum of the mean deviations was a poor predictor of secondary reflections and visual inspection of the waveforms was required.
Attenuation results of paths associated with possibly corrupted waveforms were flagged and not included in the average attenuation for that station. Also, waveforms that were clipped from insufficient dynamic range on the A/D data acquisition board were excluded.

<table>
<thead>
<tr>
<th>Cross-Correlation</th>
<th>MIN</th>
<th>MEAN</th>
<th>MAX</th>
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</thead>
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<tr>
<td>Seawater, $V_p$ (m/s)</td>
<td>1493.9</td>
<td>1500.8</td>
<td>1508.7</td>
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<tr>
<td>$\sigma$ (m/s)</td>
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<td>1.1</td>
<td>1.5</td>
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<tr>
<td>Sediment, $V_p$ (m/s)</td>
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<td>1718.1</td>
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<td>$\sigma$ (m/s)</td>
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<td>29.0</td>
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<td>Velocity Ratio</td>
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<td>1.145</td>
<td>1.209</td>
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<tr>
<td>Envelope Detection</td>
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<tr>
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<td>Filter Correlation</td>
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</table>

Table I. Summary of sound speed results calculated with the cross-correlation and envelope detection methods and attenuation results (at $f = 65$ kHz) determined using the filter-correlation method. The average of the standard deviations measured at each station is represented by $\sigma$ (MEAN).

4 Discussion of Results

A summary of the sound speed results using both methods and the attenuation results using the filter-correlation method is shown in Table I. The two methods used to calculate sound speed produced consistent results in seawater. The envelope detection method produced an increase in sediment sound speed at 84 stations, with the average increase equal to 10.8 m/s (maximum increase of 25.8 m/s and minimum increase of 0.1 m/s). A total of 13 station locations experienced a decrease in sediment sound speed, with the average decrease equal to 6.1 m/s (maximum decrease of 14.9 m/s and minimum decrease of 0.4 m/s). This method resulted in an overall average increase in sediment sound speed of 8.5 m/s for all stations. A discussion of sound speed and attenuation results and their relationship to the spatial variability of the seafloor is included in Mayer et al. [6].
Most often, the geotechnical parameter expected to exhibit some correlation with the attenuation coefficient, \( k = \alpha / f \) (in units of dB/m-kHz) is the mean grain diameter. Sediment core and grab samples were collected by investigators at the Universities of Texas and Delaware and a preliminary comparison of attenuation and grain size distribution performed (see [9] for a description of a similar grain size analysis). Comparison with published results was somewhat difficult in that published results primarily extend over a broad range of mean grain sizes [3, 10].

Station data, including grain size distributions, were sorted into descending order based on the average attenuation coefficient and divided into groups representing 0.1 dB/m-kHz decreases in attenuation. An average grain size distribution (in % fraction of sample based on weight) representing each group was determined using the grain size distributions of each station in the group. The results of this averaging process are shown in Figure 4, where each series plotted represents the averaged grain size distribution for a group of stations with similar attenuation coefficient.

Although preliminary, the averaged grain size distributions shown do present interesting results. The group of stations with the highest attenuation coefficients \((k = 0.8 - 0.9 \, \text{dB/m-kHz})\) had the largest weight percent of fine sand (1.75 to .25 mm) as well as a higher percentage of coarse grains with diameters greater than 4 mm. The group of stations with slightly lower attenuation coefficients \((k = 0.7 - 0.8 \, \text{dB/m-kHz})\), had the second largest weight percent of fine sand, the highest weight percent of grains with diameters < 4 mm, and the highest weight percent of fine grained sediments, those with diameter < 0.062 mm. In contrast, the stations with the lowest attention

![Figure 4](image-url)
coefficients had the highest weight percent of medium sand (.25 to .35 mm). These stations had grain size distributions indicating relatively, well-sorted sediments (mostly homogeneous, medium grained sands), while the high-attenuation stations contained a mixture of course and fine grained sediments.

5 Conclusions

ISSAP, a geoacoustic in-situ measurement system was used to rapidly and accurately measure compressional wave speed and attenuation in surficial marine sediments. An interesting comparison of attenuation with averaged grain size distributions was introduced. This work is in process and a more complete analysis will be presented at a later time. Continuing research will also explore the relationship between measured acoustic properties and remotely measured backscatter.

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References