ACOUSTIC REFLECTION AND TRANSMISSION EXPERIMENTS FROM 4.5 TO 50 KHZ AT THE SEDIMENT ACOUSTICS EXPERIMENT 2004 (SAX04)

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Abstract: During the Sediment Acoustics Experiment 2004 (SAX04), the reflection coefficient was measured using a three receiver vertical line array (VLA) and a source mounted on a remotely operated vehicle (ROV). Measurements at angles from 10 to 80 degrees and at frequencies from 4.5 to 50 kHz were obtained. A description of the experimental apparatus is provided. The sand/water interface was smoothed by divers and visual inspection revealed no ripple formations. Preliminary reflection coefficients for 10-50 kHz at 30 to 70 degrees are shown. Strategies are presented for determining the low angle and low frequency reflection coefficients. [Work supported by ONR, Ocean Acoustics] Keywords: Sediment Acoustics, Reflection Coefficient, Acoustic Scattering

1. INTRODUCTION

An accurate description of acoustic interaction with the ocean sediment is vital to the understanding of acoustic communication, long range propagation, mine hunting and anti-submarine warfare in shallow waters. As naval operations move to more littoral environments, understanding the bottom interface becomes increasingly more vital in SONAR applications. Even a small difference in an environmental parameter such as the sediment reflection coefficient can have a large impact in long range propagation. Also, small changes in environmental parameters can greatly impact our ability to map littoral areas or identify and classify objects on the ocean floor.

There are several models currently available to predict the acoustic interaction with sandy sediments. These include the visco-elastic model, the Biot/Stoll poro-elastic model [1][2], a grain shearing model formulated by Buckingham [3] and the Biot/Stoll Contact Squirt Flow and Shear model of Chotiros and Isakson. [4] Each model predicts different
frequency dependent behaviour of the sediment. It is important to determine which models most accurately represent the physics of the interaction for use in predicting acoustic behaviour.

Historically, the sound speed dispersion and attenuation have served as the metric for model discrimination. However, the complex reflection coefficient as a function of frequency and angle provides a third data set. Reflection coefficient measurements are ideal for the following reasons:

1. The measurements are non-invasive and relatively easy to measure over a wide range of frequencies.
2. The data can be used as direct input into shallow water propagation models.
3. It has been demonstrated that the data can be used for remote sensing of sediment parameters.[5]
4. The data contains information about other interesting physical phenomena such as interface and volume scattering.

Therefore, Applied Research Laboratories at the University of Texas at Austin (ARL:UT) made an effort to measure the complex reflection coefficient as a function of frequency and angle in situ at the Sediment Acoustics Experiment 2004 (SAX04). The test was conducted off the coast of northern Florida. The test area was similar to the area used for the Sediment Acoustics Experiment 1999 (SAX99) which has been described previously in reference [6].

2. EXPERIMENTAL SET-UP

The ARL:UT SAX04 experiment had three main measurements: angle dependent reflection coefficient measurements, acoustic sediment transmission and normal incidence reflection coefficient measurements. In this paper, only the angle dependent reflection coefficient experiment will be described.

Reflection coefficient measurements were taken using a spherical source mounted on a Remotely Operated Vehicle (ROV) and three transducers mounted on a vertical line array (VLA). The spacing on the VLA was 0.53 m, 3.28 m, and 6.02 m measured from the bottom. An additional transducer was placed at the corner of the experimental area for acoustic triangulation of the ROV position. Furthermore, a receiving transducer was mounted on the ROV above the source to measure normal incidence reflection. The layout is shown in Fig. 1.

The electronics used in this experiment can be separated into three categories: surface hardware, the submerged data acquisition system and the acoustic transducer setup. The electronic flow is shown in Fig. 2. On the surface, a PC running LABVIEW® was used to communicate via RS-232 to a data acquisition break-out box as well as the ROV control unit. The break-out box served as a RS-232 to RS-485 converter and connected to the ROV's umbilical cable and a submerged enclosure containing the receiver circuitry. The ROV is powered via switching high-current, high-voltage sources which creates an extremely noisy electrical environment. In order to minimize the electrical interference and acoustic signature of the ROV during acquisition, a computer controlled Kinetic Interrupt and Load Limiting (KILL) switch was used to temporarily interrupt power to the ROV during each acquisition.

The submerged data acquisition system utilized four custom built Digital Signal Processing (DSP) cards running on a proprietary bus based communication protocol. This protocol allowed synchronous communication between all four DSP cards and the surface computer. Each DSP card has a 40 MHz processor and four 625 kHz digital to analog converters (DAQ). One DSP card was mounted on the ROV and the other three were enclosed in an underwater container placed near the receiving transducers. The ROV based
DSP card was augmented with a gated high voltage power supply (450 VDC) and a tuning circuit to drive the sound projector. The DSP toggled the high voltage supply to create a square-wave chirp at the desired bandwidth. The tuning circuit was matched to the transmitting transducer to effectively smooth the square-wave into a regular sinusoidal chirp. The tuning circuit consisted of a tunable high-power LC circuit which was damped to provide broad resonance peaks across the frequencies of interest. It provided a 15 dB boost in the low frequency range of the transducer. Each ping was initially saved to RAM on each of the four DSP cards and then later uploaded to the PC at the surface.

![Fig. 1: The layout for the ARL:UT SAX04 experiment.](image1)

![Fig. 2: The electronic layout for the reflection coefficient experiment.](image2)

Each receiving transducer was an omni-directional ITC 1089 transducer. The transducers are cylindrically symmetric with a z axis pointing along the transducer pigtail. The transducers were positioned so that the azimuthal plane of the transducers was pointing toward the ROV. The beam patterns of the spherical transducers are nominally constant to ±1 dB azimuthally. Three separate one millisecond linear frequency modulated (LFM) chirps were used to cover the frequency range. Bandpass filtering will allow multiple sub-bands to be analyzed in each ping. This method uses one measurement to take the place of several measurements at individual frequencies. The three LFM chirps were ranged as follows: 4.5–
10 kHz, 10–22 kHz and 22–50 kHz. The lowest frequency chirp was produced using an ITC 1032 transducer. The two higher frequencies were produced using a ITC 1042 transducers. The ITC 1032 transducer could be used to produce the mid-frequency chirp as well to reduce the time necessary to change out the transducer. Normal incidence data was recorded on the receiving transducer mounted on the ROV.

It was important to cover a large angle range for the experiment especially since the location of the critical angle describes the sediment sound speed. In fact, the critical angle location over a large frequency range also describes dispersion. Also, it was critical to sample as wide of an area on the sediment as possible to insure spatial stability. It is expected that such important sediment parameters as porosity will vary across the experimental area. Fig. 3 indicates the locations of the ROV relative the VLA and navigational transducer based on acoustic triangulation. The VLA was moved once during the experiment to insure spatial stability. Almost 6000 reflection coefficient measurements were taken at SAX04 by ARL:UT. This measurement density is sufficient to provide a measurement of the subcritical behaviour as well as the critical angle and normal incidence values.

3. MEASUREMENTS

A sample of the raw data is presented in Fig. 4. The top three left hand rows are the raw signal from the three VLA transducers for the lowest frequency LFM, 4.5 – 10 kHz. The bottom row is the raw signal from the navigational transducer. The right column is the
matched filter response. The matched filter was based on the LFM signal sent to the source transducer.

The two acoustic ray paths considered in this study are the direct path and the reflected path. These are evident in the matched filtered data in Fig. 4. The direct path arrives first and is indicated by the darker red line. Based on the location of the ROV, calculated using the direct path arrival times, the arrival time for the reflected path is calculated and indicated by the light green line. A clear reflected path is observed. Any deviation from the calculated arrival time can be due to a declination of the VLA or a change in elevation of the experimental area.

Fig. 4: Sample 4.5 - 10 kHz data taken at SAX04. The top three plot rows are the VLA receivers. The bottom plots are the navigational transducer.

4. DATA ANALYSIS

The objective is to measure the complex reflection coefficient of the water-sediment interface, \( R(f, \theta) \), which varies as a function of frequency \( f \) and grazing angle \( \theta \). In terms of the projected signal \( s_p(t) \), and the far-field reflected signal \( b(t) \) from a flat interface at sufficient distance that the wave fronts may be considered as planar, it is given as,

\[
R(f, \theta) = \frac{F\{b_o(t)\}}{F\{s_o(t)\}}
\]

where

\[
b_o(t) = b(t+\tau_b/c_o)\exp(-\alpha \tau_b),
\]

\( r_b \) is the path length of the reflected signal, \( \alpha \) the frequency-dependent attenuation coefficient, \( t \) is time, and \( F\{..\} \) represents the Fourier transform. The medium above the interface is assumed to have uniform properties, with a constant sound speed \( c_o \). The term \( b_o(t) \) is the reflected signal \( b(t) \) with the propagation loss and the travel time delay removed.

In practice, if the signal bandwidth is such that \( R(f, \theta) \) and \( \alpha \) do not significantly change with frequency, then it can be approximated by,

\[
R(<f>, \theta) = \frac{\langle b_o(t) \rangle}{\langle s_o(t) \rangle}
\]

where \( \langle ..\rangle \) represent averaged values over the signal bandwidth. In the case of a rough surface, the structure of \( b_o(t) \) may be complicated and it may have to be treated as a random process.
The projected signal may be measured as a direct path signal \( s(t) \) over a path length \( r_s \), in which case,

\[
R(<f>, \theta) = (b(t-r_b/c_o)s(t-r_s/c_o))(r_s/r_b) \exp(-\alpha <f_r-r_s>)
\]

For ranges that are short such that attenuation may be ignored but not so short that wavefront curvature effects become significant,

\[
R(<f>, \theta) = (b(t-r_b/c_o)s(t-r_s/c_o))(r_s/r_b)
\]

The complex received signal, \( S_{xpn}(t) \), which may be obtained by a Hilbert transformation of a real signal, is considered as the sum of the direct path \( s_{xpn}(t) \) and the bottom reflected \( b_{xpn}(t) \) signals, where the subscript “\( x \)” indicates that the signal has been modified by scattering by medium inhomogeneities and angle dependent beam patterns of the source and receiver; “\( p \)” and “\( n \)” denote the ping number and the receiver channel number, respectively.

\[
S_{xpn}(t) = s_{xpn}(t) + b_{xpn}(t)
\]

In general, scattering will cause amplitude, phase and travel time fluctuations. Assuming that the correlation time of the scattering was large compared to the travel time of the signals, and that the correlation bandwidth is also larger than the signal bandwidth, then the scattering may be modeled as multiplying factors \( a_{xpn} \) and \( a_{bpm} \) for the amplitude and phase deviations, and random time fluctuations \( \tau_{xpn} \) and \( \tau_{bpm} \), that may be treated as constants within one ping cycle.

\[
s_{xpn}(t) = a_{xpn}s_{opn}(t-\tau_{xpn}-r_{xpn}/c_o)/r_{xpn}
\]

\[
b_{xpn}(t) = a_{bpm}b_{opn}(t-\tau_{bpm}-r_{bpm}/c_o)/r_{bpm}
\]

where \( s_{opn} \) and \( b_{opn} \) are the direct and reflected signals in a perfectly uniform water medium, after accounting for the spreading losses; \( c_o \) is the sound speed; \( r_{xpn} \) and \( r_{bpm} \) are the corresponding path lengths. Attenuation will be ignored due to the short distances involved, but it can be incorporated later if necessary. The direct signal \( s_{opn} \) is repeatable from ping to ping because it is determined by the sound projector hardware. The reflected signal \( b_{opn} \) may be subject to random variations because the reflection surface may be rough.

Lastly, the reflection coefficient is given by the ratio between \( b_{opn} \) and \( s_{opn} \).

\[
R_{pn}(t) = b_{opn}(t)/s_{opn}(t)
\]

This time ratio can be determined at the peak of the matched filter correlation for the direct and reflected paths. The grazing angle is determined from the position of the ROV which can be found using the direct path travel times to the VLA receivers and the navigation transducer.

This analysis will be complicated by interface roughness and volume inhomogeneities which are undoubtedly present in real ocean sediments. They will cause random variations in the reflection coefficient and a bias that will be frequency dependent.

The reflection coefficient measurements for the 10-22 kHz and 22 – 50 kHz data sets are shown in Fig. 5. The 4.5 – 10 kHz data are not shown. These data include significant headwave effects which must be corrected. The analysis of this data is beyond the scope of this paper and will be shown in subsequent publications. The data are compared with a visco-elastic model of flat water-sediment based on a sediment sound speed of 1740 m/s,
attenuation of 0.486 dB/m/kHz and density of 1.99 kg/m$^3$. The modeled water speed was 1500 m/s with a density of 1.032 kg/m$^3$.

**Fig. 5: Reflection Coefficient Data for 10 - 22 kHz (a) and 22 - 50 kHz (b).**

At low grazing angles, the matched filter correlation peaks for the direct and reflected paths overlap, making it difficult to determine the reflection coefficient. These data are not included on the plots. For low grazing angle data, the direct path must be isolated and subtracted from the time series.

The direct path signal can be extracted from an ensemble average, relying on (i) the direct path signal is the first to arrive, and (ii) the bottom reflection, averaged over a suitable range of angles and positions, is a zero mean random process. This requires averaging reflected data from independent parts of the bottom and over a range of grazing angles, such that, when the direct path signals are aligned, the reflected path signals will average to zero. Although there may be significant overlapping, there will always be a small part of the direct path signal that arrives ahead of the bottom reflection. If these first arrivals are aligned and normalized, then the direct path time series, its arrival time and its relative amplitude can be determined. Fig. 6(a) shows the alignment of raw time series for the mid receiver. After about 300 μs, the reflected signal begins to arrive indicated by the variability in the measurements. In Fig. 6(b), the direct paths for the three VLA receivers for the 4.5 – 10 kHz pulse are shown. Although the first few cycles are identical, the pulses deviate at higher frequencies, due to the differences in the directivity of the source and differences in the response of each receiving hydrophone. Furthermore, the direct path for the lowest phone shows evidence of headwave interference.

**Fig. 6: Figure (a) shows the alignment of the raw time signals to obtain the direct path for the mid receiver. The heavy black line indicates the average. Figure (b) shows the direct path for the three receivers.**

The next steps for analysis are: 1) Separation of direct and reflected path signals and matched filtering for low grazing angle, 2) Correction of the reflection coefficient for spherical wave
effects and scattering and 3) Comparison of the data with current acoustical models. These topics will be addressed in subsequent publications.

5. CONCLUSIONS

Reflection coefficient measurements were made on a sandy sediment at the Sediment Acoustic Experiment 2004 (SAX04). Measurements were made from 4.5 to 50 kHz at grazing angles from 10 to 80 degrees. The data will provide a third data set in addition to sound speed and attenuation measurements for sediment model discrimination. While most models can be fine-tuned to fit pressure and shear wave speed and attenuation measurements very few models can fit reflection measurements as well. All these measurements together allow better model discrimination. The data also provides an alternate method of determining dispersion. The data were collected using a three receiver VLA and a source mounted on an ROV. A large angle range of data and many spatially independent samples were collected. The higher grazing angle reflection coefficient data were computed from the data for the 10-50 kHz frequency range. The low grazing angle range required the subtraction of the direct path. A method for direct path isolation was determined and demonstrated. The next steps for analysis are the analysis of the low grazing angle data by reflected path isolation and the determination of the influence of scattering and spherical wave effects in the data.

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