

# HIGH-FREQUENCY ACOUSTIC PROPAGATION IN THE PRESENCE OF OCEANOGRAPHIC VARIABILITY

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Broadband mid-to-high frequency (0.6-18 kHz) acoustic wave propagation in shallow coastal waters (< 20 m) is influenced by a variety of oceanographic conditions. Physical parameters such as temperature and salinity as well as hydrodynamic parameters such as surface waves, tide and current can influence amplitude and travel time of signal transmissions. In this paper a unique set of simultaneous ocean and acoustic observations that reveal interesting temporal behavior of the acoustic signal and its correlation with environmental variability are presented. The temporal variations in salinity, including those induced by the semi-diurnal tides and a northerly wind event, are accurately predicted by using the measured acoustic signals and temperature profile.

## 1 Introduction

Environmental variability, especially in shallow coastal regions, can cause amplitude and phase variations in acoustic signal propagation over different time and space scales. The cause-and-effect relationship between fluctuations in the ocean environment and those in the received acoustic signal needs to be better understood. Although studies over the past few years have made significant progress, more work needs to be done to fully capture the complexity and variability in shallow-water environment.

In 1997 a high-frequency broadband acoustic propagation experiment was conducted at a very shallow site in the Delaware Bay. The location of the experiment (shown in Fig. 1) was chosen in an area that observations could be conducted unobstructed for long periods. During the same period, a parallel research in characterizing the oceanography of the bay was conducted at the same location. The combined results from these two concurrent observations have provided an interesting opportunity in which oceanographic features such as salinity or temperature fronts could be observed directly by using the propagation of the acoustic signals.

In this paper we first present a description of the oceanography in this shallow-water acoustic waveguide. Then the acoustic wave propagation is qualitatively related to controlling factors of the environment, in particular to the frequently observed salinity features resulting from fresh water input in coastal regions. The frequency range of probe signals was 0.6-18.0 kHz which overlaps with that of the underwater acoustic communications signals.



Figure 1: Map of the experiment location.

## 2 Shallow water Oceanographic Features observed in Delaware Bay

Delaware Bay is a major coastal plain estuary located on the east coast of the United States. Previous studies have shown that the bay is forced by a combination of tide, wind, and river induced motion [1]. The spatial and temporal variability associated with these mechanisms can have significant implications for the transmission of acoustic signals in the bay, thus providing an opportunity to field concurrent and calibrated oceanographic characterization and acoustic propagation tests. In this section, we provide a description of oceanographic features observed during a one-week period in September 1997.

Figure 2 shows the temporal variability in wind speed and direction as well as the vertical profiles of current, salinity, and temperature at the study site. For the sake of brevity, only the longitudinal component of the current will be considered here. The temporal variation in the observed current is dominated by the semi-diurnal lunar (M2) tide. The amplitude of the M2 current (about 45 cm/s) decreases slightly with depth, but the phase of the M2 current shows little variation with depth, indicating barotropic motion from surface to bottom. The diurnal tides are also present in the Delaware Bay, but the amplitude of the principal diurnal solar tide (K1) is about an order of magnitude weaker than that of M2.

In addition to the tidal variability, the current also exhibits non-tidal variability which operates over several-day time scales. The non-tidal current has a standard deviation of only about 1.2 cm/s, even though its magnitude may exceed  $\pm 3$  cm/s at times. The non-tidal current is largely forced by winds acting either over the surface of the bay or over the continental shelf adjacent to the bay. The record-mean distribution

of the current profile shows a two-layer circulation, with outflow at the surface and inflow in the lower layer.

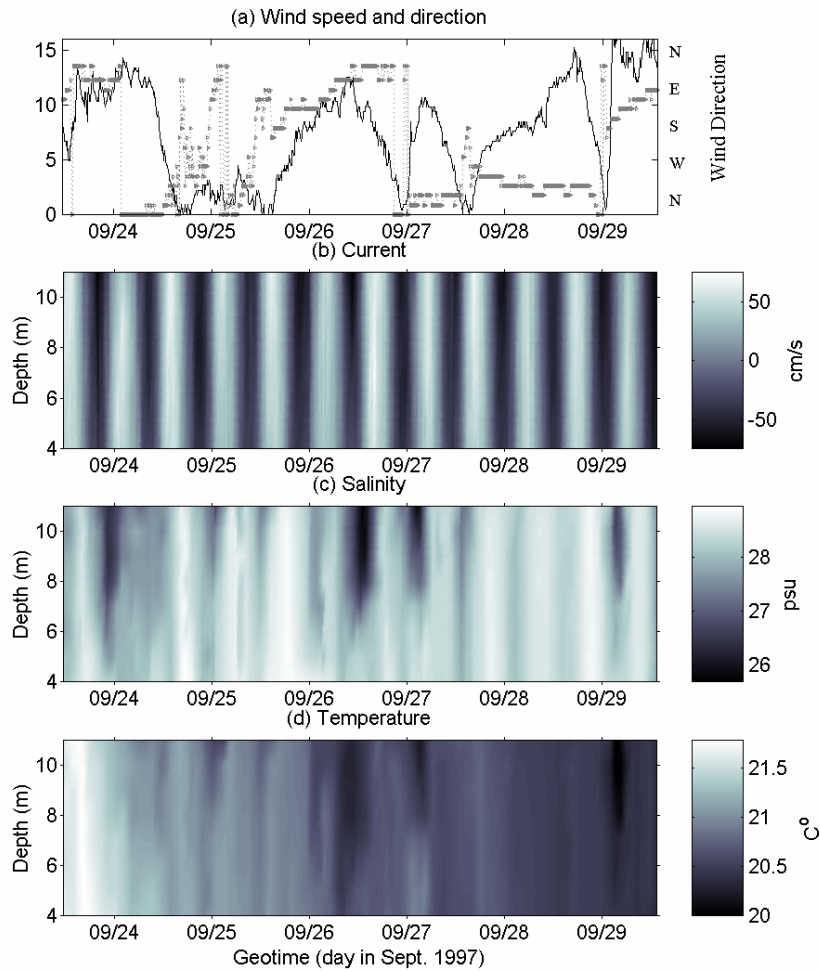


Figure 2: Oceanographic measurements in Delaware Bay during September 23-29, 1997; (a) Wind speed (solid line) and direction (dotted line) measured above the surface, (b) current profile, (c) salinity profile, (d) temperature profile.

Even though the magnitude of the mean flow and the non-tidal current variability is small, the low frequency process is important to the long-term transport and distribution of waterborne material in the bay.

The temporal variability in the current structure has a profound influence on the salinity distribution. The mean salinity distribution shows that the lower bay was weakly stratified during the study period, with a surface to bottom salinity difference of only 0.6 practical salinity units (psu). Similar to the current, the salinity also shows tidal and non-tidal variability on top of the mean distribution. Again the M2 tide dominated the salinity variability, and the semi-diurnal variation in salinity is 90 degrees out of phase with that in current, indicating that tidal advection plays a significant role in determining the salinity structure. The quadrature phase between current and salinity indicates that salinity is lowest at the time of slack water after ebb, and the highest salinity value is found at slack water after flood. The amplitude of the M2 salinity variation is largest near the surface (0.5 psu) and smallest near the bottom (0.12 psu). This indicates that the water column becomes most stratified at slack after ebb, and the water column is least stratified at slack after flood.

This ebb-flood asymmetry in the degree of stratification may be in part explained by the effect of tidal straining [2]. Given the larger tidal current amplitude near the surface than near the bottom, the upper part of the water column will experience a greater tidal excursion than the lower part of the water column over a tidal cycle. Assuming that the background longitudinal salinity gradient remains constant during the tidal cycle, the differential tidal excursion between the upper and lower parts of the water column will tend to intensify the surface to bottom salinity difference at the end of the ebb cycle. The reverse occurs at the end of the flood cycle, as the differential advection will reduce the surface to bottom salinity difference then.

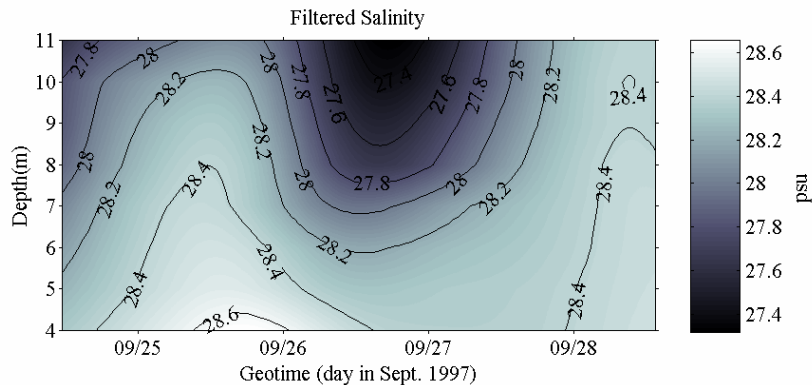


Figure 3: non-tidal salinity variation for the week of experiment.

The data shows that salinity can undergo substantial non-tidal variation of up to 0.8 psu over 2 to 3-day time scales. This salinity variation is closely associated with wind events, such as the one on September 26 (see Fig. 2 and 3). On that day the wind was

primarily from the north, and this wind caused a non-tidal advection of low salinity water from the upper part of the estuary into the lower bay. The temporal variations in salinity, both at the tidal and non-tidal time scales, can have a significant impact on the transmission of acoustic signals in the lower bay.

### 3 High Frequency Acoustic Wave Propagation Experiment

A description of the oceanography of the experiment location was given in the previous section. To capture the physical parameter variability in the changing water column a one-week acoustic observation was conducted. Two fixed tripods, each having an acoustic source and three receiving hydrophones, were placed in 15 m of water separated by 387 m. The source was located 3.125 m above the sea floor and transmitted chirp signals over the frequency range of 0.6-18.0kHz. The three receiving hydrophones were located at 0.33, 1.33 and 2.18 m above the sea floor, respectively.

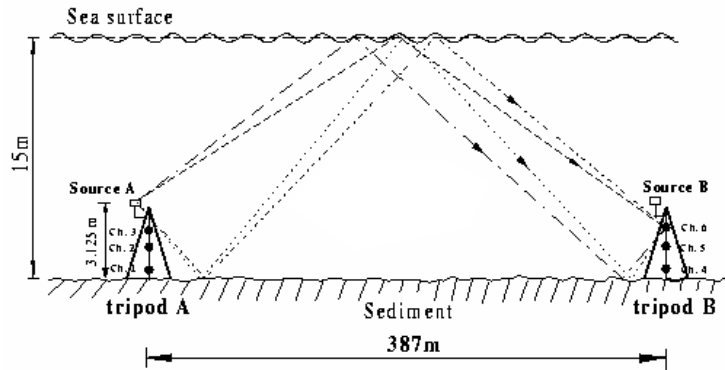


Figure 4: Acoustic experiment set up.

To sample different scales of temporal variability in the experiment two different pulse transmission rates were used. In the first case a chirp signal was transmitted every 0.345 seconds for a five second period and repeated every ten minutes for the entire week. In the second case the same chirp signal was transmitted every 0.345 seconds for a 40-second interval and then repeated every hour for the entire duration of the experiment. In both cases the signal was received locally (by the three hydrophones attached to the same tripod as the acoustic source), as well as by the three remotely mounted hydrophone receivers (located 387 meters away). The 5-second sampling, repeated every ten minutes, was useful for studying the minutes-to-hour acoustic fluctuations due to sound speed changes in the water column, while the 40-second sampling, repeated hourly, was useful for analyzing the fast acoustic fluctuations due to surface waves. It is also noted that in both sampling cases each received signal has sufficient time to clear before the next signal arrives so that overlap between adjacent signals did not occur.

The acoustic signal following different ray paths arrives in groups of echos. The first group consisting of the energy arriving from direct and single bottom bounce paths (which arrive so close in time as to interfere and form a single peak); the second group consisting of energy following four rays having one surface bounce. The third group consisting of energy from four rays with two surface bounces; and so forth [4-5]. The first group represents acoustic energy that has not interacted with the sea surface, while all other groups consist of arrivals from rays that have one or multiple interactions with the sea surface. Fluctuations of the first group can be correlated with variations in the ocean current and the sound speed while fluctuations of later arriving groups also include the effects of variations of the tide height and sea surface roughness. The detailed reference for the group dynamics and the other analysis is found in [4-5].

For analysis here, we focus our attention on one of the ray paths that has only interacted once with the sea surface. We are able to separate the path by beamforming at the receiver array. Figure 5 shows for a specific geotime the beamformed signal for first two groups of arrivals. In this figure, there is a clear and distinct arrival at approximately  $0^\circ$  in arrival angle, corresponding to the first group having no sea-surface interaction. After that, there are four dominant and distinct arrivals corresponding to the four ray paths that comprise a group of arrivals, all having only a single sea-surface interaction. We consider one of these ray paths that interacted with sea surface once and arrived earlier than the rest (designated by dashed line in Fig. 5). Tracking this ray over the period of observation, provides a depth averaged sound intensity that has traveled through the upper water column.

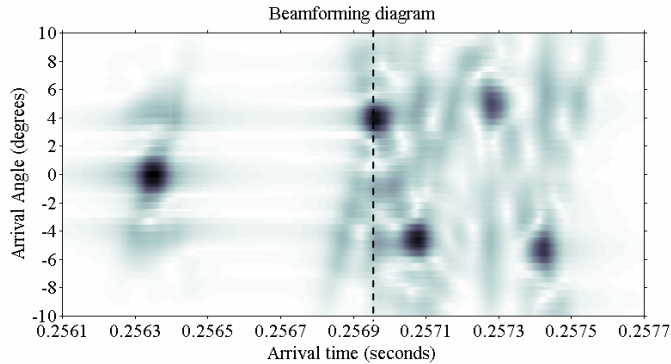


Figure 5: Acoustic pressure beamforming for a specific geotime.

## 4 Methodology

In this section a brief explanation of the methodology that was used to acoustically track the aforementioned salinity feature is provided. Transmitted pulses are first beamformed at the vertical hydrophone receiver array [5]. Then using the selected ray path and a

known source-receiver geometry, one can calculate the sound speed as  $C_{calc} = R/t_a$  where  $R$  is the travel distance of the ray and  $t_a$  is the ray arrival time. The travel distance of the ray is related to the source-receiver depth, distance, and the water depth that are all known accurately in this experiment.  $C_{calc}$  is a depth-averaged sound speed across the water column from the source to the sea-surface. Based on an empirical formula to calculate the sound speed from salinity and temperature profiles [3] the following equation can provide the salinity if sound speed and temperature are known

$$S(C_{calc}, T) = 35.0 + \frac{C_{calc} - 1449 - 4.6T + 0.055T^2 - 0.00029T^3}{1.34 - 0.01T} \quad (1)$$

where the salinity  $S$  (psu), the sound speed  $C_{calc}$  (m/s), and the temperature,  $T$  (°Celsius) are all time dependent quantities. Using (1) the salinity is obtained for the entire week of the experiment from the acoustic propagation given the measured temperature profile. Figure 6 shows the comparison between the acoustically obtained values of the salinity and the direct measured values using CTD (see Fig. 2.c.) in geophysical time (geotime) for the entire week.

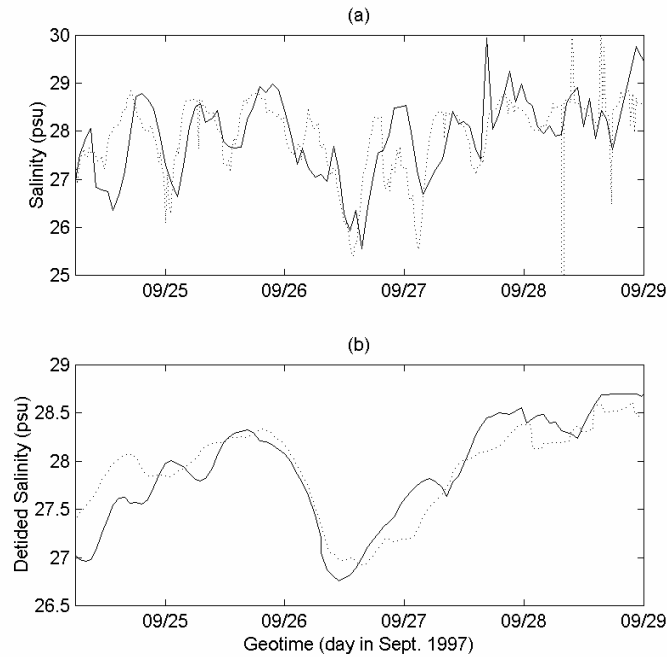


Figure 6: Comparison between predicted and measured salinity, (a) Raw data, (b) Filtered data to outline the non-tidal variations of the salinity. The solid line represents acoustically predicted value of salinity and the dotted line shows the measured value 2m below the sea surface.

A running averaged window can enhance the comparison results by eliminating the tidal effects (Fig. 6.b).

## 5 Summary

Concurrent oceanographic and acoustic observations were conducted in shallow water region of Delaware Bay. The purpose of these tests was to understand the correlation between the oceanographic features and the high frequency acoustic wave propagation. Results show a direct (cause and effect) relationship between salinity and temperature changes with acoustic wave propagation in shallow waters. Separating a single ray path by beamforming technique the temporal variations of the salinity are detectable from the measured temperature and acoustic transmissions.

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