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OBSERVATIONS OF HIGH FREQUENCY, LONG RANGE ACOUSTIC PROPAGATION IN A HARBOR ENVIRONMENT

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Abstract: *The positioning and navigation of AUV's in harbor environments using underwater acoustics is complicated by shallow waters, long propagation distances, and complex oceanographic features. This paper reports on high frequency (40 kHz) acoustic measurements made in Portsmouth Harbor, NH, USA, which is an estuary containing several riverine inputs and a strong tidal flow (2+ knots). A one-way propagation experiment was conducted at the mouth of the harbor for propagation distances up to 100 water depths. Strong signatures of a variety of phenomenon were observed in the acoustic signal levels, including tidal heights and currents, turbulent mixing, and wind/wave action. The relative importance of each of these will be discussed in terms of signal to noise level and the associated constraints on acoustic positioning systems.*

Keywords: *acoustic positioning*

1. INTRODUCTION

Many aspects of harbor security involve the ability to acoustically track AUVs or other targets in the complex environment of the coastal zone. This can be challenging due to the dynamic conditions caused by shallow water, turbulent mixing, fast currents, and large tidal variations. Traditional methods of AUV positioning combine measurements of the vehicle's velocity with its heading to obtain its position. Typical methods for measuring speed include speed through water sensors, Doppler velocity logs, or inertial navigation systems, all of which suffer from drift, and require initial positions as well as frequent trips to the surface to get GPS position fixes (Leonard et al. [1], Whitcomb et al. [2], Titterton and Weston [3]). The need for surface positioning fixes poses additional problems in a harbor setting because of interference with ship traffic. The addition of acoustic positioning could alleviate the need for frequent excursions to the surface, thereby increasing operational time and minimizing potential interference with other vessels. Typical methods of underwater acoustic positioning include short baseline (SBL), long baseline (LBL) and ultra-short baseline (USBL) positioning. USBL positioning uses a combination of phase differencing and range measurements over a short (< 1 meter) baseline to determine the position of a mobile transponder (Vickery [4]). SBL is similar, except that the hydrophones are more widely spaced (5 – 20 meters) and make measurements of the time of arrival instead of phase differencing (Milne [5]). LBL systems measure travel times between several widely spaced, bottom-mounted transponders in a fixed network. Once the relative positions of these transponders is known, they can be used to position a moving pinger. LBL positioning solutions often incorporate a least squares algorithm to solve for the positions of the transponders in the network as well as the moving target (Deffenbaugh et al.[6], Wikström et al.[7]). SBL and USBL methods typically require the use of a surface vessel with hull mounted transducers. Conversely, LBL systems, with their fixed, semi-permanent transponders, would be well suited to long-term monitoring.

In this study we explore the viability of using an LBL system to provide long range (approximately 1 kilometre) acoustic positioning of underwater vehicles or sensors. Making shallow water range measurements presents challenges that are not usually an issue in deeper water operations. In deep water, long range solutions such as LBL have proved to be reliable largely because the assumption can be made that the entire array of acoustic transponders is contained within a layer of constant sound speed (Milne [5], Vickery [8]). Deep-water range measurements can be estimated using a sound speed measurement at one location and extrapolated to the entire area. In contrast, harbors are often extremely shallow, with strong tides and currents, where simplifying sound speed assumptions cannot be made. Mixing between fresh river water and saline ocean water causes turbulence and inhomogeneities in the sound speed structure, leading to incomplete knowledge of the acoustic ray paths through the water.

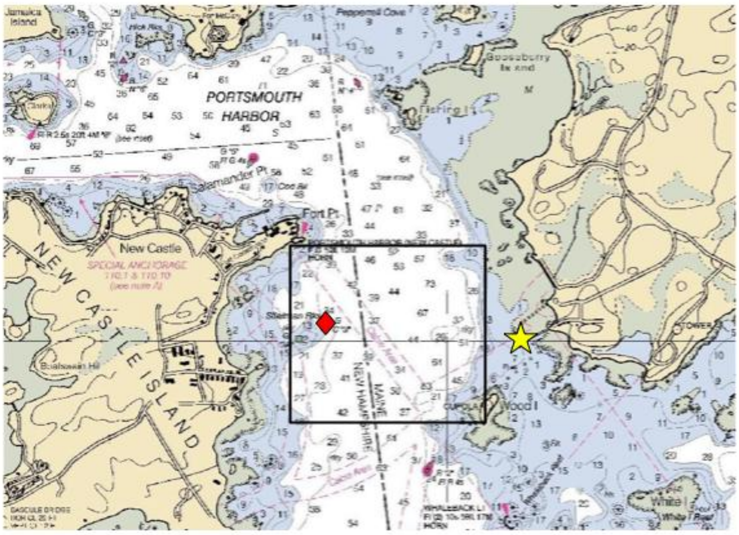

Fig.1: Chart of Portsmouth Harbor showing the area of interest, including the source (diamond symbol) and the receiver (star symbol). The source and receiver are approximately 950 meters apart, with an average depth across the transect of 10 meters.

In October 2007, a one-way acoustic propagation experiment was carried out in Portsmouth Harbor to investigate the capabilities and limitations of long-range, shallow water time of arrival detection for acoustic positioning. The experiment utilized two fixed transducers: a bottom-mounted source, and a receiver mounted on a pier piling at Fort Foster, on the east side of the channel (Fig. 1). The source and receiver were separated by a distance of approximately 950 meters. Acoustic range measurements were made over four days, for several hours each day to observe the effects of current, tide, sound speed structure, and wind speed. Together, measurements of these variables reveal an extremely complex environment in which to make acoustic time of arrival measurements.

2. ENVIRONMENTAL DATA

Sound speed data was collected over four days of acoustic measurements using three different methods: a Seabird CTD profiler, a CTD chain [9], and an Odom Digibar sound velocimeter. On the first three days of the experiment, the Seabird CTD profiler was used to measure sound speed profiles along the transect between the source and receiver. Between three and five sound speed casts were made every half hour, generally within ten minutes of each other to capture large scale spatial variations from one side of the harbor to the other. These transects showed variability of several meters per second from one side of the harbor to the other within the few minutes that it took to complete the transect. All of the sound speed profiles collected using the Seabird CTD profiler are shown in Fig. 2.

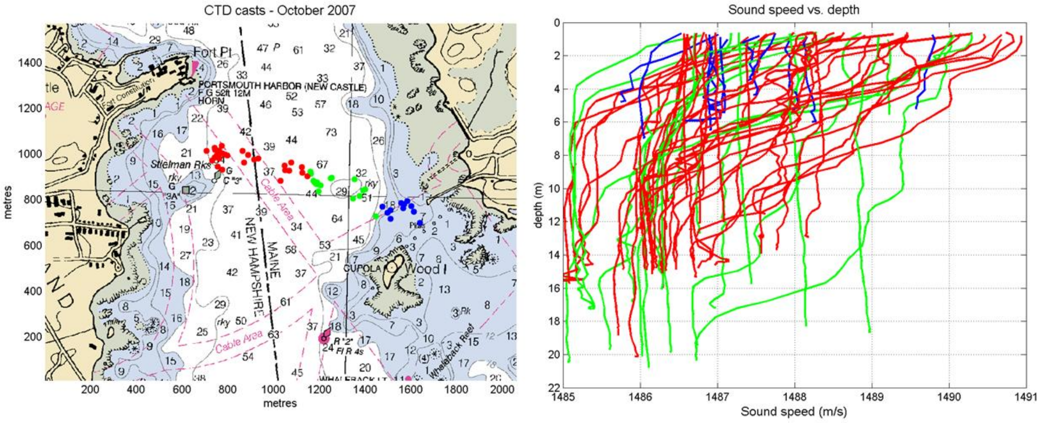

Fig.2: The image on the left shows the locations of all of the CTD casts measured during the four days of data collection. The corresponding sound speed profile data is shown in the plot on the right. The colors on both plots correspond to the general locations in the harbor. The red color shows profiles in the sand wave field on the west side of the channel. The green color shows profiles in the deepest part of the channel. The blue color shows profiles in the shallow rocky areas near the hydrophone array.

On the fourth day of the experiment, the survey vessel was anchored in the middle of the channel so that a CTD chain could monitor the sound speed fluctuations with depth over several hours. The CTD chain measured the sound speed at a rate of 1 Hz through the entire water column using 18 individual sensors. While the CTD chain was deployed, the Seabird CTD profiler measured full water column casts in the same location every half hour.

The CTD chain data showed large variability on short time scales. Sound speed changes on the order of 5 m/s occur over time scales of less than half an hour. Fig. 3 shows the temperature data from both the CTD chain and the CTD profiler.

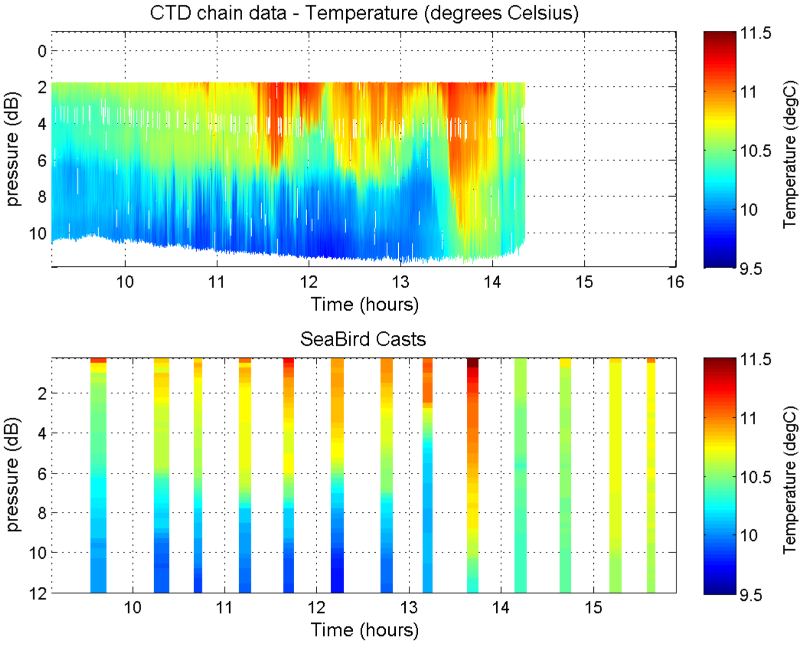

Fig.3: CTD chain and Seabird CTD profiles measured on 26 October.

The Digibar sound velocimeter was mounted near the hydrophones on a pier piling at Fort Foster. It measured sound speed over the four days of data collection. It was located in the relatively shallow water and although it might not be representative of the sound speed across the harbour, it provides a continuous sound speed record at one location. The variability at this one location was greater than 5 m/s over the four days (Fig. 4).

The complexities observed in the sound speed structure are due in part to the tidal currents that bring water masses in from the ocean and down from the upper estuary. Tide height data was obtained from a NOAA tide gauge at the Fort Point Coast Guard station, approximately 1.5 km upriver from the experiment area. The diurnal tides showed a range of greater than three meters at the time of the data collection, which is a significant fraction of the ten-meter average depth in the area. Tidal current predictions were made using ADCP current data gathered during May and June 2007, and showed currents in the harbor reaching speeds of more than 60 cm/s.

There was very little wind during this experiment, with the exception of a few hours on the first day (23 October). The increase in wind speed was verified using data from the Isles of Shoals weather station located ten miles offshore to the south-east of the experiment site. On this day, the wind measured at the Isles of Shoals reached speeds of nearly 15 m/s (30 knots) from the south. Breaking waves and increased wave heights were observed around the onset of the ebb flow, where the general current direction was south, into the wind.

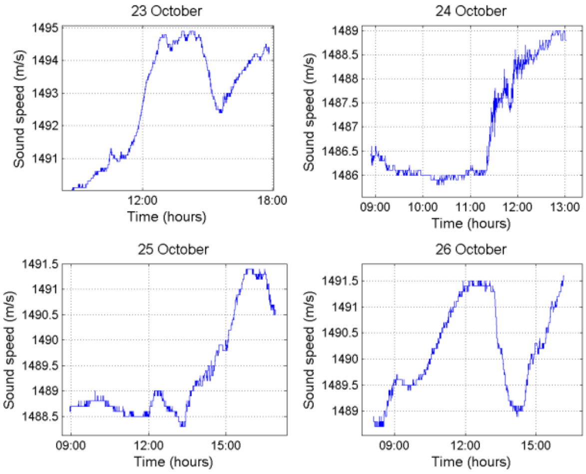

Fig.4: Digibar sound speed velocimeter measurements for all four days of data collection. The Digibar sensor was mounted on the Fort Foster pier piling near the acoustic receiver.

3. ACOUSTIC DATA

Acoustic measurements were made using a Reson TC-4013 hydrophone mounted on a pier piling at Fort Foster (Fig. 1). An acoustic source was bottom-mounted in a weighted frame at a distance of approximately 950 meters across the channel. The source was a SensorTech SX-30 free-flooded ring transducer, with an omni-directional beam pattern in the plane perpendicular to the axis of the ring. It was linked via cable to a surface buoy containing the pinger electronics and a GPS receiver. The GPS 1 pulse-per-second signals were used to synchronize the transmit and receive times to enable accurate time of arrival measurements.

The transmit pulse used in this experiment was a stepped chirp consisting of seven 1 ms CW pulses in 1 kHz steps from 37-42 kHz, transmitted at a 1 Hz repetition rate. A matched filtering algorithm was used to process the acoustic data in Portsmouth Harbor. This type of signal detection is commonly used to detect signals in noise. The matched filtering operation is accomplished by cross-correlating the known transmit signal s(t) with the received signal x(t) (Equation 1). It assumes that the received signal contains a version of the transmitted signal, possibly attenuated. The maximum of the cross correlation output y(t) gives the time delay and amplitude of the signal (Burdic [10]). If the received signal has been deformed as a result of turbulence or interactions with the surface or bottom, the peak amplitude may be lower.

$$y(t)=\int_0^T x(t)s(t)dt \tag{1}$$

The peaks of the cross-correlator output for each ping are shown in Fig. 5. An estimate of the sound speed along the travel path, combined with a time delay measurement can provide a range estimate. In the simplest form of acoustic range estimation, refraction and sound speed variability are not considered, and the acoustic ray is assumed to have travelled in a straight line from source to receiver. The sound speed is assumed to be constant along the travel path. In this simple case, the travel time can be converted directly into an estimate of range. Since both source and receiver in this experiment are stationary, the travel time in a non-refracting environment should appear as a straight line. This does not appear to be the case in the cross-correlator output. For any given measurement time, there are two to three distinct arrivals, and none of them form a straight line. The earliest arrivals appear to be monotonically decreasing on 23, 25, and 26 October. The spacing between the arrivals on all three days appears to be decreasing as each day goes on. Perhaps the most problematic feature for acoustic range estimates are the gaps that occur in the first arrivals, such as those on 25 and 26 October, where the first arrivals disappear for several hours at a time. The average spread in the time of arrival measurements corresponds to a total range spread of approximately five to seven meters using the Digibar sound speed measurements.

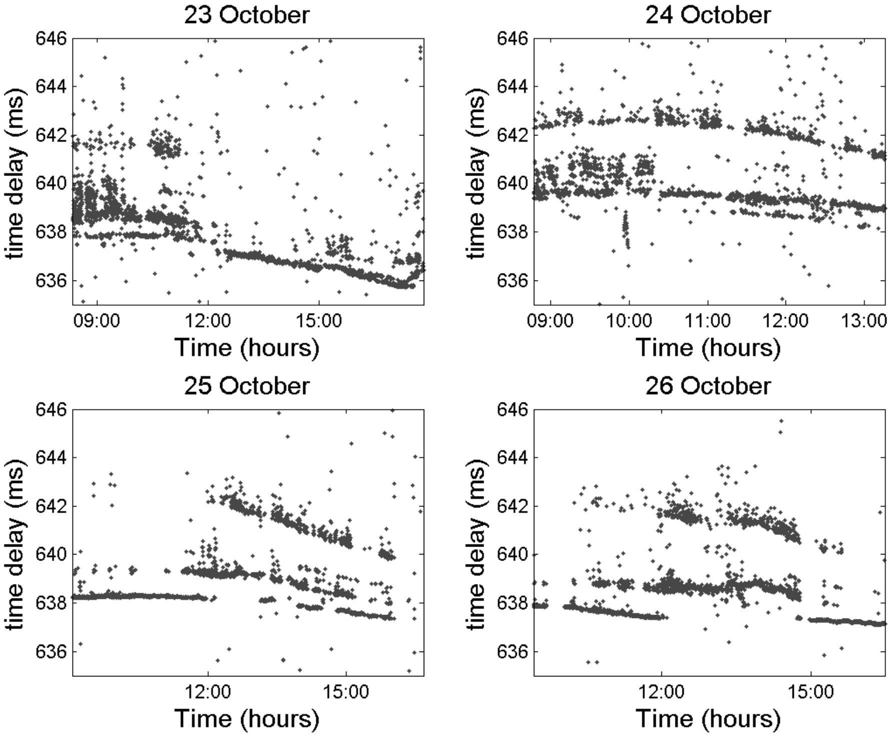

Fig.5: Arrival times in milliseconds based on picking the maximum of the output of the matched filtering operation. Several distinct groups of arrival times are visible on each day, and sometimes the first arrival disappears and reappears for hours at a time.

The deviations from a constant travel time seen in Fig. 5 may be the result of changes in sound speed. The most continuous record of sound speed depth profiles is the CTD chain data collected on 26 October (Fig. 3), and the relationship between this data record and the acoustic measurements was examined. The way in which the sound speed might affect the acoustic data is divided into two categories. First, the harmonic mean sound speed, or the average sound speed through which an acoustic ray travels, might change over time, causing variability in the measured delay time. Second, the level of stratification in a shallow channel will affect whether a direct path arrival is possible. If the water is well-mixed, there will be less refraction and signal arrivals will have fewer boundary interactions.

The CTD chain data shows large variations in the sound speed over very short time scales. If this data were representative of the sound speed along the entire transect between source and receiver, then it would be reflected in the time of arrival data. The data from 26 October does not show any strong signatures that indicate that delay time is affected by the sound speed measured by the CTD chain. For example, a sharp change in the depth-averaged sound speed of 5 m/s occurs at around 13:30h in the CTD chain data (Fig. 4). If this change were occurring throughout the entire harbor, the resulting change in arrival time would approximately 2 milliseconds. This change in arrival time is not present in the acoustic data (Fig. 5), which means that the sound speed fluctuations measured at the CTD chain location are not representative of the sound speed over the entire travel path. The general trend of the depth-averaged sound speed does, however, show a slow increase in sound speed over the day. This might explain the gradual decrease in arrival time of the first arrival observed on all of the days of data collection.

The overall level of stratification in the CTD chain data appears to increase gradually until just before noon, and at that point, a sharp increase in the level of stratification is observed. This corresponds approximately to the disappearance of the first arrival in the acoustic data. The CTD chain data record ends shortly after 14:00h, however an additional three CTD casts were measured over the next 1.5 hours. Since the CTD casts matched well with the CTD chain data when they were measured concurrently, the CTD cast data after that point is believed to be reliable. It shows a decrease in stratification that corresponds to the reappearance of the first arrival in the acoustic data. These results indicate that the short time scale fluctuations occurring in the sound speed at a given point in the harbor are not necessarily reflected in the sound speed data across the entire channel. Instead, the gross sound speed stratification seems to play a more important role in that it affects the number of interactions a given ray will have with the surface and bottom.

4. CONCLUSIONS

The environmental measurements show that Portsmouth Harbor is a very dynamic environment, with a large tidal variation, strong tidal currents, mixing between fresh water and sea water, and very shallow bathymetry. Positioning AUVs using acoustic ranging is challenging in a complex environment such as Portsmouth Harbor. The rapid variations in the sound speed are difficult to measure, and full understanding of propagation paths would require constant, closely spaced sound speed measurements.

Despite the complexities, however, the short time-scale variability observed in the sound speed measurements does not appear to affect the time of arrival measurements. Instead, the large-scale sound speed trend, as well as the overall level of stratification in the water column appear to dominate the major trends in the acoustic data.

Based on the preliminary time-of-arrival estimates (Fig. 5) along with sound speed measurements taken in the harbor, simplified range estimates can be made with an accuracy of between five and seven meters.

5. ACKNOWLEDGEMENTS

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