Acoustic positioning and tracking in Portsmouth Harbour, New Hampshire

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Abstract—Portsmouth Harbor, New Hampshire, is frequently used as a testing area for multibeam and sidescan sonars, and is the location of numerous ground-truthing studies. Having the ability to accurately position underwater sensors is an important aspect of this type of work. However, underwater positioning in Portsmouth Harbor is challenging. It is relatively shallow, approximately one kilometer wide with depths of less than 25 meters. There is mixing between fresh river water and seawater, which is intensified by high currents and strong tides. This causes a very complicated spatial and temporal sound speed structure. Solutions that use the time-of-arrival of an acoustic pulse to estimate range will require very precise knowledge of the travel paths of the signal in order to separate out issues of multipath arrivals. An alternative solution is to use the phase measurements between closely spaced hydrophones to measure the bearing of an acoustic pinger. By using two bearing measurement devices that are widely separated, the intersection of the two bearings can be used to position the pinger. The advantage of this approach is that the sound speed only needs to be known at the location of the phase measurements. Both time-of-arrival and phase difference systems may encounter difficulties arising from horizontal refraction due to spatially varying sound speed.

I. INTRODUCTION

Portsmouth Harbor, New Hampshire is the location of numerous hydrographic and seafloor characterization projects including single beam, multibeam, sidescan and LiDAR surveys (e.g.,[1], [2], [3]). Ground truthing of seafloor type has been accomplished in many areas using still cameras, video cameras, and also by collecting physical samples for laboratory analysis ([4], [5]). In addition to vessel-based studies, there is growing interest in the use of remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) for seafloor mapping. In heterogeneous environments like Portsmouth Harbor, a high positioning accuracy (< 1 m) for these underwater sensors/vehicles is required in order to match the positioning accuracy of, for example, a vessel-mounted multibeam sonar. The goal of this research is to identify the most cost-effective, accurate underwater positioning methodology, suitable for an environment like Portsmouth Harbor, and to estimate the fundamental limits on the positioning accuracy for the various methods.

A typical method for positioning AUVs is to integrate the vehicle’s velocity over time to provide position [6]. The speed can be found using a speed through water sensor, or if the operations are close enough to the seafloor, a doppler velocity log can measure the speed-over-ground [7]. A heading measurement is also required to update positions. The problem with using a speed-through-water sensor is that it cannot differentiate between the speed of the vehicle and the currents in the area. Doppler velocity logs do not suffer from this problem, but there is significant drift over time as the velocity is integrated to solve for position. Inertial navigation systems (INS) can also be used [8]. INSs combine measurements of acceleration and direction and use a double integration to determine position. These systems are self contained and do not require communications with an external source, however, they do need an initial position at the start of the survey. They provide good positional accuracy, but are often cost prohibitive and are also problematic for battery operated systems due to their high power consumption.

Underwater vehicles can also be positioned using acoustic techniques such as ultra-short baseline (USBL), short baseline (SBL), and long baseline (LBL) positioning ([9], [10], [11]). USBL uses phase differencing measurements between closely spaced (< 1 m) hydrophones [11] to estimate the direction and elevation angle of an incoming signal. These are combined with travel time measurements to estimate range for pinger positioning. SBL is based on a similar concept, except that the hydrophones are more widely spaced (5 - 20 m) and instead of phase differencing, time difference of arrival is used [9]. Both USBL and SBL systems are commonly mounted on vessel hulls, but can also be moored on the bottom [12] or mounted in buoys at the surface [13]. LBL systems measure travel-times between an array of transponders and a moving pinger. With multiple travel time, or range measurements, a least squares
algorithm can be used to estimate the position of the pinger using either a hyperbolic or spherical solution ([14], [15]).

These acoustic positioning systems can be reduced to two fundamental measurement types: time-of-arrival detection and phase differenting. Time-of-arrival measurements are made for estimating range or range differences. These measurements require estimates of the sound speed along the travel path in order to solve refraction and multipath issues. For this reason, time-of-arrival measurements are often suited to deep water environments where the entire array is generally contained within one sound speed layer. Phase differenting measurements are used to detect the direction of an incoming signal. The advantage of phase differenting measurements is that the sound speed is only required at the location of the hydrophone array. Both time-of-arrival and phase difference systems may encounter difficulties arising from horizontal refraction due to spatially varying sound speed.

These measurement types are being examined individually in order to separate uncertainties in each. By isolating them in controlled experiments, the fundamental limits in each of the positioning methods can be analyzed to build uncertainty models for the acoustic measurements in Portsmouth Harbor.

II. PHASE-DIFFERENCING HYDROPHONE ARRAY

In order to examine the accuracy of phase differencing systems, a prototype system was developed, consisting of three hydrophones mounted on a rigid steel plate. By taking phase difference measurements between the two hydrophones, the incoming angle of the signal could be estimated. Bearing estimates become more accurate as the distance between the two hydrophones increases [16]. On the other hand, increasing the spacing between the hydrophones increases the number of ambiguities in the measured phase difference once they are separated by more than half a wavelength [16]. To resolve these ambiguities, the three hydrophones worked together in pairs. The system was designed to operate at 40 kHz, with the closer hydrophones spaced at 2/3 wavelengths apart and the more widely spaced hydrophone pair separated by 5 wavelengths. To fully resolve ambiguities, the hydrophones would need to be spaced at half a wavelength or less apart. For hydrophones spaced 2/3 wavelengths apart, the effective field of view is restricted to approximately +/- 49° from broadside.

For an initial test, the hydrophone array was installed on the Coast Guard pier at Fort Point on Newcastle Island. The hydrophone array was mounted to a piling as shown in Figure 1. To measure a bearing in the earth's reference frame, the orientation of the hydrophone array relative to north needed to be measured. This was done by mounting a GPS receiver on the piling directly above the hydrophone array. This receiver logged position for several hours. The GPS receiver was then moved to the other side of the pier to a second piling so that the two GPS positions and the plane of the hydrophone array was parallel.

To test the bearing measurement system, a pinger was installed on a vessel in the harbor. It was positioned using GPS with real-time kinematic (RTK) corrections. The GPS position of the pinger was logged at each transmit time. Since the position of the hydrophone array and the pinger were known at the time of each ping, the true bearing could be calculated. This was used as a comparison for the phase-difference bearing solution. The GPS receivers also provided time synchronization between the hydrophones and transmitter by using the 1 pulse per second signal as a trigger. A radial survey pattern centered on the array was chosen for the vessel so that lines of constant bearing could be followed (Figure 2), allowing for a more systematic examination of bearing and its relation to range. Periodic sound velocity measurements were taken using a conductivity/temperature/depth (CTD) sensor. These showed a warmer surface layer with a drop in sound speed of approximately seven m/s in the top three to four meters of water.

A coarse bearing measurement was estimated first for
each phase-differenced signal using the closely spaced hydrophones. The difference between the true bearing and the coarse phase-differencing measurement had a standard deviation of 1.25° for angles up to 20°. The coarse bearing measurement was used to resolve the ambiguity in the solution for the widely spaced hydrophones. This resulted in a fine bearing measurement with a standard deviation of 0.3° for angles up to 20°. The accuracy of the bearing measurements degraded significantly when the signal-to-noise ratio fell below 15 dB, so values less than 15 dB were not included in these calculations. The accuracy of both coarse and fine bearing measurements decreased as the angle from broadside increased, which is a result of the decrease in effective array spacing. This is because the projection of the hydrophone array onto the planar wavefront decreases as the cosine of the bearing angle.

As a result of the fact the horizontal distances traveled by the signals were much larger than the average water depth, there was a high likelihood that the signals arriving at the hydrophones were multipath arrivals. If the signal arrives from anywhere other than the horizontal plane that intersects the hydrophone array, it will induce a bias error in the bearing estimate. The size of the error depends on the elevation angle and the bearing. Figure 3 shows a model of how the elevation angle affects the bearing estimate, and the only regions where the bias error is zero are those where the elevation angle of the signal is zero degrees, or when the signal arrives at broadside. The bias increases rapidly with increases in either azimuth angle and elevation angle.

The errors caused by incoming signals that are not horizontal must be accounted for in some way before attempting to resolve the bearing angle through phase differencing. If there is reasonable confidence that the incoming signals are close to horizontal, then the errors will be minimized, however, this may not be the case in our area of study.

III. A CABLE-TO-SHORE HYDROPHONE ARRAY

In January 2007, the phase-differencing hydrophone array was moved to a more permanent location near the entrance to Portsmouth Harbor, approximately 100 m east of the lighthouse at Fort Point in 8 m of water. The submerged part of this cable-to-shore installation was built on a 400 kg base and consisted of three hydrophones, a conductivity and temperature sensor, signal conditioning electronics, and a small computer. Power and data communications utilized a multi-conductor underwater cable connecting the submerged hydrophone system with a ‘topside’ computer housed inside the lighthouse. A wireless Ethernet system provided connectivity with the outside world, enabling the complete system to be controlled from any internet accessible location.

The three phase differencing hydrophones were configured in exactly the same way as described above for the August 2006 array, with two closely spaced hydrophones for resolving the phase ambiguity and the widely spaced hydrophones for the fine bearing measurements. The node is capable of acting as either a range (time of flight) or a bearing measurement node, or both at once.

Testing in February 2007 focused on determining the useful range for this system by transmitting signals at increasing distances and measuring the received signals and SNR at each (Figure 4). Figure 5 shows that the 10 ms pulses transmitted at 40 kHz had SNR values of at least 22 dB, which exceeded the minimum SNR of 15 dB as determined during previous experiments. These results are promising, showing strong returns even from distances over 1300 meters along the shallow west side of the harbor. The average depth in this area is only 10-15 meters, so the signals were still easily detected after traveling over 100 water depths. CTD measurements were made concurrently, and showing a well-mixed structure, very different from the sound speed measurements made in August. The total gradient in the sound speed from top to bottom was no more than 2 m/s over 10 m depth at any of the measurement locations.

IV. FUTURE WORK

Experiments have been designed for late summer and fall 2007 that will expand on previous work. A series of portable autonomous pingers have been built that can be deployed from a small boat or moored on the bottom. These bottom mounted pingers will transmit continuously over several days, while sound speed and current data is collected simultaneously. The transmit signal will alternate between a continuous wave (CW) pulse and a frequency modulated (FM) pulse for the phase differencing and range measurements, respectively. The effect of the environment, specifically currents and sound speed, will be measured and analyzed concurrently with acoustic measurements of both range and phase in order to detect any relationship that may exist between the environment and the accuracy of the range and bearing measurements.
REFERENCES


