A Versatile Tracking System for AUV Testing

Doug Odell, Jesse Pentzer*, John Canning*, Dean Edwards*
Acoustic Research Detachment, 33964 N. Main Street, Bayview, ID 83803
*Center for Intelligent Systems Research, University of Idaho, Moscow, ID 83844-1024

Abstract- **Testing and development of AUVs and AUV-based systems can be greatly accelerated with access to a suitable underwater tracking range area. A tracking system was recently developed jointly by the NSWCCD Acoustic Research Detachment (ARD) and the University of Idaho (UI). Located on Lake Pend Oreille, the system is used routinely to test AUVs being developed at UI. The system includes four acoustic tracking nodes which are held stationary near the lake floor. Three transducers are mounted on each node and cabled to a dockside tracking and control station. Acoustic pings are emitted from the test vehicle at periodic intervals. These pings are received at multiple tracking nodes allowing 3-D tracking solutions to be computed. The test area covers approximately 23,000 square meters, with a nominal water depth of 15 meters.**

The system is versatile enough to accommodate special testing needs and changing user requirements. Tracking nodes can reply back to the AUV, emulating a transponder recognized by onboard navigation systems. Tracking can be synchronous (known ping time) or asynchronous (unknown ping time). Many different ping waveforms are supported, over a broad range of frequencies. System components and capabilities are discussed, along with unique features and attributes. Tracking performance is discussed and test results are presented.

Operating the tracking system is very cost-effective. The system is easily accessible and can be quickly set up and broken down. This allows a paradigm shift in AUV development where less time is spent developing simulation software in favor of time spent performing in-water testing.

I. INTRODUCTION

A versatile acoustic tracking range system has been developed to support AUV testing in shallow water. The system supports onboard AUV navigation, produces 3-D track, and performs other useful functions. This system was developed jointly by the NSWCCD Acoustic Research Detachment (ARD) and the University of Idaho (UI), and was funded by the Office of Naval Research (ONR). ARD is part of the Naval Surface Warfare Center, Carderock Division.

The tracking range is located at the south end of Lake Pend Oreille, Idaho, and covers a tracking area of approximately 23,000 square meters. Nominal water depth is 15 meters. The system includes four bottom-mounted tracking nodes. Each node contains 3 transducers: a broadband hydrophone, low-frequency projector, and high frequency projector. Nodes can receive, transmit, and/or emulate a transponder. Each node is buoyed 3 meters above the lake floor and is cabled to a central topside tracking and control station.

An acoustic baffle plate is mounted directly beneath the transducers to suppress reflections from the node structure and the lake bottom. Precise knowledge of node location is needed for accurate tracking and navigation. A unique self-survey technique is used to determine the location of each tracking node. This highly accurate survey, combined with accurate ping detection algorithms, can yield topside track with (seemingly) unprecedented accuracy. The accurate survey also improves onboard AUV navigation performance.

The vehicles currently utilizing the tracking system are small scale AUVs approximately 1 m long and 10 cm in diameter based on a design by Dan Stillwell et. al. of Virginia Tech. The vehicles have successfully demonstrated fleet behaviors related to cooperative mine hunting in previous testing [1]. These behaviors are being utilized to enable a fleet of AUVs to perform a magnetic signature measurement of a surface ship [2].

Two of the University of Idaho AUVs have been modified to carry a tri-axial fluxgate magnetometer and a data acquisition system as shown in Fig. 1. This has enabled the vehicles to measure three orthogonal magnetic field components over a range of ±100,000 nT while operating underwater.

The magnetic measurements recorded on an AUV must be tagged with a position relative to the ship in three dimensions within 1 m of the true position of the AUV. This positioning accuracy is needed to model the magnetic signature of the ship accurately using the recorded measurements. The tracking system has been used extensively for the optimization of navigation algorithms used in real-time and post-processing [3] while also serving as the acoustic transponders needed by the AUVs to navigate.

This paper discusses the major components of the tracking system along with key features and attributes. Operation of the system is described and test results are provided. Conclusions and future work are also discussed.

Figure 1. AUV equipped with external magnetometer during initial pool testing.

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II. BACKGROUND

Acoustic tracking in the shallow-water environment is particularly challenging. Acoustic tracking signals (pings) received at hydrophones are immersed in a barrage of multipath interference (echoes). Tracking requires reliable detection of acoustic signals (pings) and precise measurement of ping arrival time. Also needed are accurate knowledge of sound-velocity and accurate positions of stationary tracking transducers.

Multipath interference is the nemesis of shallow water tracking. It occurs when acoustic reflections (echoes) from the transmitted ping interfere with the intended direct-path reception. This interference causes position errors and loss of track. Reflections come from many sources such as the lake surface, lake bottom, tracking node structure, vehicle hull, etc. As the AUV moves through the tracking range, the multipath structure at each hydrophone changes. During AUV testing, the primary source of multipath interference is the lake surface. Surface-bounce multipath varies with surface conditions (waves). AUVs operate at shallow depths so the time delay between direct-path reception and surface-bounce receptions is shorter than the ping waveform itself.

The lake bottom in the tracking range area is composed of sandy silt which can attenuate the reflected energy by greater than 20 dB, but this depends on the angle of incidence. This attenuation, also termed the forward reflection loss, approaches zero (dB) as the grazing angle approaches zero [4]. This becomes an important consideration during the self survey process discussed in section IV.

Another major source of tracking error arises from sound velocity errors. An accurate estimate of sound velocity is needed to convert measured acoustic propagation delay (time-of-flight) to distance (range). Errors in sound velocity are typical and create bias errors in range measurements. These bias errors are proportional to the measured range which can lessen the impact for small range areas. Also, these bias errors vary slowly as the vehicle moves through the range area and therefore have less effect when measuring vehicle motion between successive pings, or when measuring distance between two vehicles in close proximity.

Sound velocity changes with temperature, pressure, and salinity. Changes in water temperature, caused by weather fluctuations, significantly alter the sound velocity profile. Sound velocity is normally measured in a vertical water column with a CTD profiler. These devices measure conductivity, temperature, and pressure. Sound velocity is then computed using empirically-derived models [5,6]. The effective sound velocity between any two depths is computed using a harmonic mean technique which averages the time delay through the water column, as opposed to averaging the velocity itself.

Vehicle motion creates Doppler shift in received pings. The shift is proportional to vehicle velocity in the direction of each transducer. For matched-filter ping detection algorithms, Doppler shift can reduce the correlation of the incoming waveform with the stored replica. The chosen Doppler compensation technique employs multiple replicas, each having a different Doppler-shift, and each simultaneously correlated with the input signal. An example correlation output is shown in Fig. 2. As Doppler changes, the peak moves left or right across the Doppler indexes, while keeping the same general shape. This technique also provides a Doppler estimate for each ping detected.

III. COMPONENTS AND CAPABILITIES

Fig. 3 shows the operational area of the tracking range. The range includes four submerged tracking nodes, labeled A-D. This location is within the protected area of ARD and has a nominal water depth of 15-20m. The tracking area measures approximately 150 meters across. This small-scale tracking range is suitable for operating small AUVs. Cables connect each tracking node to a central control station located under a covered boat dock (seen as the rectangular structure to the left of node D). The proximity of nodes A and B was chosen, not for optimal tracking, but to accommodate a special test. These nodes will later be relocated for more optimal tracking.

A representative tracking node structure is shown in Fig. 4. The structure is approximately 2.6 m tall. Three transducers are shown at top. The grey panel below the transducers is an anechoic plate made of Syntactic Acoustic Damping Material (SADM) produced by Syntech Materials, Inc. This panel measures 0.75 m across and suppresses acoustic reflections from the node structure and the lake floor. The yellow block is floatation made of syntactic foam. An aluminum tube extends downward. An anchor (not shown) is connected to the bottom of the tube by a short cable. Upon deployment, the unit floats directly above the anchor, to a height of 3 m. The acoustic panel is held horizontal to provide a 360-degree (acoustic) look angle.

Each tracking node is cabled to a topside tracking and control station. Table I lists the major hardware components.

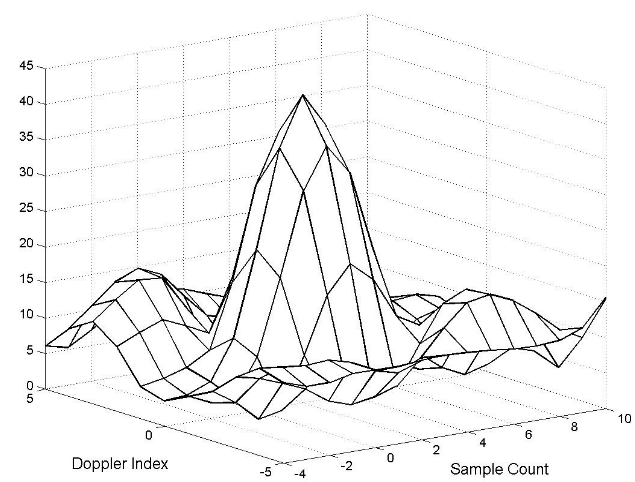

Figure 2. Correlation output for PSK signal having zero Doppler.

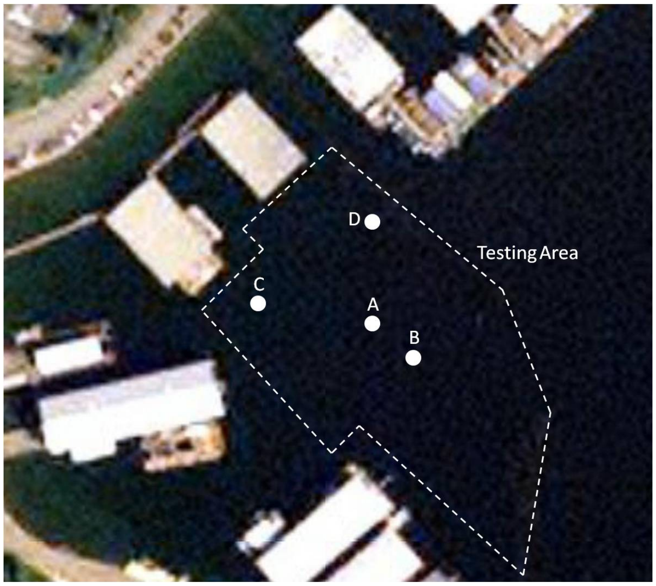

Figure 3. Tracking range area with tracking node locations shown.

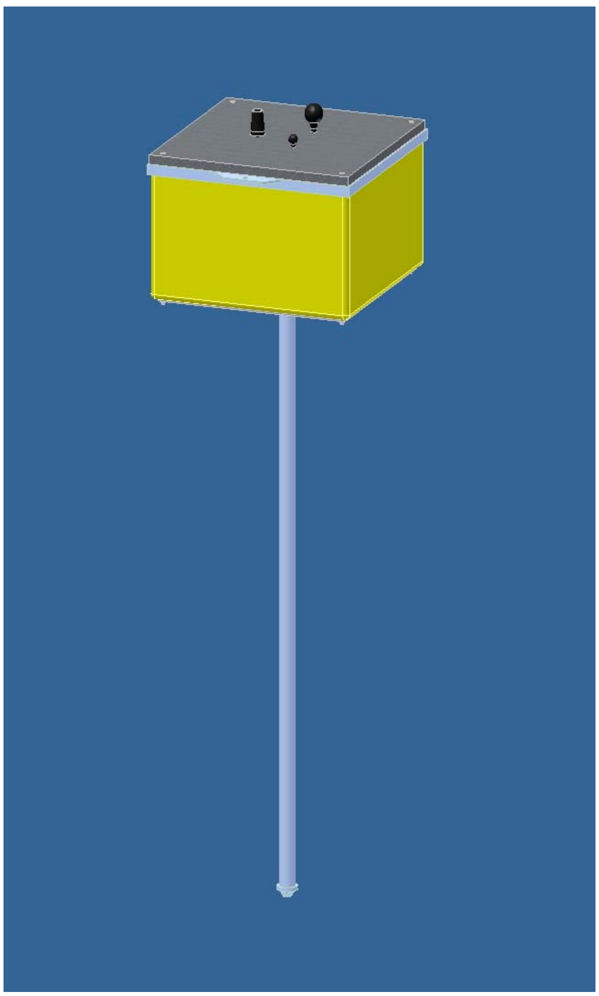
Figure 4. Submerged tracking node, showing transducers.

TABLE I
MAJOR HARDWARE COMPONENTS

Hydrophones	International Transducer Corp, Model 8140 (4)
Projectors (low-frequency)	International Transducer Corp, Model 1032 (4) (20-50kHz)
Projectors (high-frequency)	Wilcoxen, HSP100 (4) (50-100kHz)
PXI Chassis	National Instruments, PXI-1045 (18 slot)
Chassis Controller	National Instruments, Model 8106
Data Acquisition Cards	National Instruments, PXI-4462 (2)
Timing Cards	Symmetricom, bc637CPCI (1), bc635CPCI (4)
Arbitrary Waveform Generators	Stategic Test, UX6011 (4)
Power Amplifiers	Instruments Inc., Model L2 (4)

The real-time software has three major components: ping detection, tracking, and hardware control. Of these the ping detection module is the most complex and the most computationally intensive. The software can be configured for several useful modes of operation using a set of configuration and setup files.

Ping detection software runs as a separate task on the chassis controller. To minimize processor loading, hydrophone signals are first translated to base-band, filtered, and decimated. Processing is done in the frequency domain whenever possible for efficiency. Matched filter algorithms correlate the incoming signals with stored replicas of the ping waveforms. Detection decisions are made when the correlation output exceeds a selected threshold. Ping time-of-arrival is measured by locating the precise center of the correlation peak.

Leading-edge processing is also common in underwater tracking systems and is used to detect narrow band signals such as tone-burst and frequency shift keyed (FSK) waveforms. This method uses a band-pass filter followed by amplitude detection. Leading-edge techniques are less accurate than correlation techniques, but can be more robust to multipath interference.

The tracking is not without problems. The system currently exhibits unexpectedly high surface-bounce interference which was causing the direct-path reception to often be missed in favor of the surface bounce. This phenomenon is still being diagnosed but the expected cause is a deployment malfunction causing two of the tracking nodes to lean at unacceptable angles. To combat this multipath anomaly, the acoustic detector algorithm was augmented to utilize a combination of correlation and leading-edge techniques. Correlation is used to detect the signal. Then the leading-edge processing separates the direct path arrival from the surface-bounce.

After each ping is detected, a UDP packet containing the arrival time and other necessary information is broadcast on the network. This allows topside track display on multiple computers. Multiple tracking solutions are computed in real-time to accommodate different user requirements.

Topside tracking is performed using long-baseline techniques. The distance from the AUV to each tracking node is determined from the measured acoustic propagation delay and the effective sound velocity. Topside tracking algorithms are written in MATLAB and utilize iterative least-squares techniques to locate the 3-D position which most closely agrees with the ping arrival time at each hydrophone. The MATLAB Instrument Control Toolbox is required for TCP/UDP support. This approach allows multiple engineering displays to operate simultaneously from different computers on the network. The software supports synchronous (known ping time), or asynchronous (unknown ping time) tracking.

The data acquisition cards are slaved together so that all channels are sampled simultaneously. To provide an accurate time reference, a 1PPS signal is sampled on an unused channel. Anti-alias filtering performed by the sigma-delta converter produces a smoothed pulse at the ADC output. The leading-edge of each sampled pulse is located in the data stream to provide a periodic timing reference. Interpolation between sample points is used to increase accuracy.

To support AUV navigation, each node can be configured to emulate a transponder. This enables the AUV to determine position using round-trip (2-way) time-of-flight measurements. A timing card, arbitrary waveform generator (Arb), and power amplifier are dedicated to each node. When a navigation ping is received at a hydrophone, a specific reply ping is transmitted back to the AUV. The reply waveform is first loaded into the Arb, and a precise trigger time is programmed into the timing card. When the trigger time arrives, the reply is then transmitted automatically. The time delay between the received ping and the reply ping is a fixed value of 200ms.

The system can accommodate different ping waveforms and different frequencies. Phase-shift keyed (PSK) pings are common and include a pseudo-random code sequence, referred to as the ID code. ID codes allow multiple AUV operations where each vehicle transmits a unique ID code. To accommodate unknown Doppler shift of the received ping, multiple replicas are used, each shifted by a different amount. The detection software simultaneously correlates the received signal with all Doppler shifted replicas.

Linear frequency modulated (LFM) waveforms are useful for stationary objects where no Doppler exists. LFM waveforms are used to measure distance between tracking nodes during the self-survey process described in section IV.

IV. Self-Survey of Tracking Node Transducer Locations

During deployment of tracking nodes, we obtain an approximate node location using GPS position of the deployment barge and estimates of lake depth. The angular orientation of each node is unknown. The acoustic self-survey provides precise 3-D positions as well as the angular orientation of each tracking node.

The tracking range is designed and laid out so that pings emitted from one node can be received on all others. Each node is pinged to determine the distance between nodes. Since each node has a separate hydrophone and projectors, the bidirectional measurements between two nodes will differ. Pings are also bounced off the surface to measure depth.

The high-frequency projectors and the hydrophones are used during the survey. The high-frequency projector allows broader bandwidth waveforms which reduce error in range measurements.

A Cartesian coordinate system is used for the survey and for subsequent tracking. A coordinate within the test area is chosen as the origin. The Z axis points downward to be more consistent with depth. The surface level of Lake Pend Oreille varies up to 3 m seasonally. The Z axis zero was set to the "full pool" summer lake level. To maintain a right-hand coordinate system the X axis was aligned with the North direction and the Y axis aligned with the East direction.

The self-survey is performed in five distinct steps:

1. Independent depth measurements
2. Measure distance between nodes
3. Compute self-consistent positions
4. Compute angular orientations
5. Align self-consistent survey to real-world coordinates.

The first step is to independently measure the depth of each node by bouncing acoustic pings off the surface of the lake and then receive the pings on the node that transmitted. Calm surface conditions will improve this process. Approximately 100 measurements are averaged to minimize error caused by surface waves. A short PSK ping is used for this measurement. Surface conditions can de-correlate the reflected waveform making longer pings difficult to detect [7]. The surface level of the lake is carefully recorded at the time of the measurements and also on each subsequent day the tracking range is used.

In the second step, bidirectional distance measurements are made between each pair of tracking nodes. Care is taken to obtain the best possible accuracy. The lake floor is the primary source of multipath interference. Because the nodes are close to the bottom, the resulting bounce arrives a few hundred microseconds after the direct arrival. This multipath arrival creates a second and undesired correlation peak which distorts the first peak and creates measurement error. The amplitude of the bottom-bounce is partially attenuated by the lake floor and the acoustic panel. Because the grazing angle is so slight, the forward reflection loss from the lake bottom is low [4]. Additionally, the small angular difference between the direct and reflected path will limit the attenuation realized by the acoustic panel. The bandwidth of the ping waveform controls the width of the correlation peak. For this measurement, the correlation peak must be narrow enough so that the desired first peak can be accurately resolved. An LFM ping with 30kHz bandwidth and 5ms duration was constructed for these measurements. Compared to PSK waveforms, the autocorrelation of LFM waveforms exhibit lower side-lobe levels, which helps to minimize measurement error.

During the third step, self-consistent positions for all tracking nodes are computed. On each tracking node, the arrangement of transducers is identical and the spacing between transducers is precisely known. On each node there exists a midpoint between the hydrophone and projector. These become the initial survey points for each node. For each pair of nodes, the average of the two bidirectional measurements is computed, which is also the distance between these midpoints. With four nodes, there are six unique measurements. The Z coordinate for each node was determined in step one. A temporary coordinate system is created in which one node is at the X-Y origin and another node lies on the X axis. This leaves 5 remaining unknowns. An iterative least-squares algorithm is used to compute the self consistent locations. The algorithm solves a system of nonlinear equations using a gradient decent method. This optimization problem in many dimensions is discussed in [8]. Given more measurements, six, than unknowns, five, a residual error can be computed which indicates the accuracy of the fit. This is useful to identify erroneous measurements.

The fourth step is to solve for the angular orientation of each node. Here, the difference between each pair of bidirectional measurements along with the self-consistent locations derived in step three are used. A separate but similar least-squares algorithm computes the angular orientation of each node. This algorithm is somewhat temperamental. A plethora of local minimum and maximum exist which give false solutions. With six measurements and four unknowns, a residual error can be computed to identify these false solutions. A simple trial and error approach is used, where solutions are attempted using randomly chosen initial angles, until the correct solution is identified. With all angles then determined, the location of each transducer can be calculated within the temporary coordinate system.

The final step is to align the self-consistent positions to real-world coordinates in the X-Y plane. For this, two points on the tracking range are chosen where both tracked position and GPS position are measured. Coefficients are then calculated which allow the temporary coordinate system to be rotated and translated to bring the tracked and GPS positions into agreement. To obtain the position data a transducer (pinger) is suspended from a boat to a fixed depth. The boat is tied to a dock or moorage on a calm day. A GPS antenna is mounted directly above the pinger to allow latitude and longitude to be recorded. Many successive pings (10-100) are emitted and positions are averaged.

V. AUV Testing and Performance Results

The topside tracking system has been used extensively for AUV testing. The system provides real-time track of the AUV location, while simultaneously providing replies to acoustic navigation pings sent out by the vehicle. Fig. 5 shows data from a representative test. The solid black line is the output of a post-processing navigation algorithm described in [3], and the red markers are topside tracking solutions that occurred approximately every two seconds. For the run shown, the

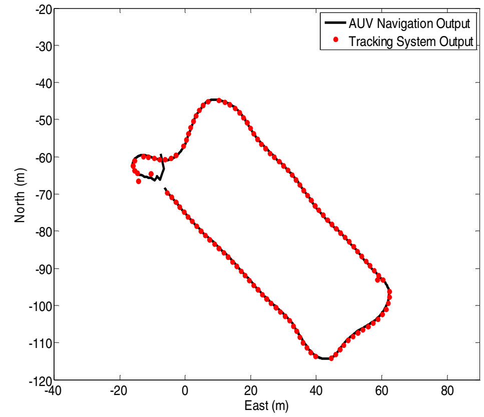

Figure 5. AUV path returned from post processing navigation algorithms with corresponding tracking output.

average difference between the topside solutions and post-processing estimate was 0.42 m. The accuracy of the tracking system has allowed it to be used as a baseline to optimize against. Utilizing the tracking solutions in this way has reduced navigation errors on the AUV from approximately 1.0 m to 0.3-0.4 m.

Tracking accuracy can be measured in different ways. One common method is to compare acoustic track to GPS position. However, when AUVs are submerged, GPS position data is unavailable. Another approach is to compare the relative position of two or more pingers which are held at a constant separation.

A test was conducted where two pingers were held at a fixed separation and towed slowly through the tracking range. Both pingers were tracked independently, and the resulting 3-D separation was compared to the actual separation. A simple test fixture was constructed using PVC pipe. Transducers were attached to each end of the fixture and held at a fixed separation. This device was then suspended at a constant depth and towed slowly through the test area.

PVC was chosen for its acoustic transparency which minimizes unwanted reflections. Care was taken to remove any air bubbles from the test fixture, as these can create significant reflections. Dockside measurements showed the actual separation to be 2.87m.

Pings were emitted at one second intervals with different waveforms emitted from each transducer. For this test a PSK ping with 127-bit ID code, 33kHz bandwidth, and 8ms duration was created. The high bandwidth, code length, and duration were chosen to improve tracking accuracy. This relationship is discussed by Burdic [9], and confirmed with test results. Separate ID codes allowed independent track of each pinger.

The fixture was towed endwise, with one pinger following the other. A 1-PPS pulse was used to trigger both outgoing pings. One ping was delayed by 25ms to lessen interference at the tracking nodes. During towing, this delay causes a small but predictable error in the tracked separation.

Fig. 6 shows results from this test. The vertical axis is the separation and the horizontal axis is ping time. The black line shows the 3-D separation from raw tracking data. The blue

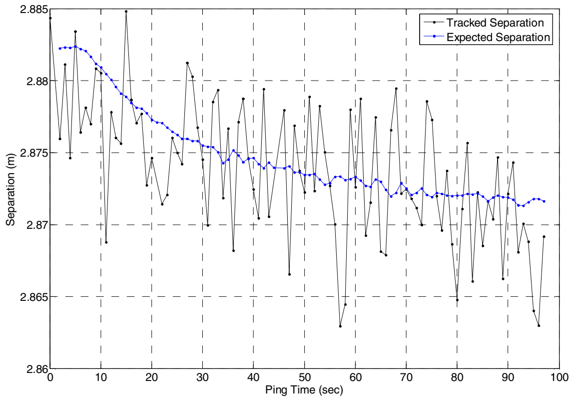

Figure 6. Tracking accuracy, 3-D separation, PSK33127.

line shows the expected separation, based on the dockside measurement and corrected for tow speed. Tow speed was determined from the acoustic track. During this test, the tow speed varied slightly creating the slope seen in the figure. Note that random variation in tracked separation, about the expected curve, is approximately 0.01m.

As a second part to this test, an alternate PSK ping waveform was used for comparison. This is the navigation ping currently used by the AUV. It has 28-bit ID code, 8.1kHz bandwidth, and 7ms duration. Results are shown in Fig. 7. This test produced less accuracy and was more vulnerable to multipath interference, creating many more outliers (not shown).

Unfortunately, conditions differed between the two parts of this test, making a direct comparison somewhat subjective. Technical difficulties on test day precluded towing during this portion of the test. The fixture remained stationary near the deployment dock, where tracking is normally less accurate.

VI. FUTURE WORK

Based on technologies developed for this tracking range, a second and larger tracking range is currently under development. The new range will be located further from shore and in deeper water to support magnetic signature measurements of surface vessels. The current tracking range is near large metal pilings and barges. This creates magnetic noise which contaminates measurements. The new range will include five tracking nodes arranged in a pentagonal pattern. Nodes will be separated by 150 to 300 m. Nominal water depth is 150 m. The new range will have a primary tracking area in excess of 200,000 square meters, centered about the tracking nodes. Large surface craft can operate in this area, allowing magnetic signature measurements in a magnetically clean environment. Tracking outside this area will also be possible, but accuracy and reliability will degrade with distance.

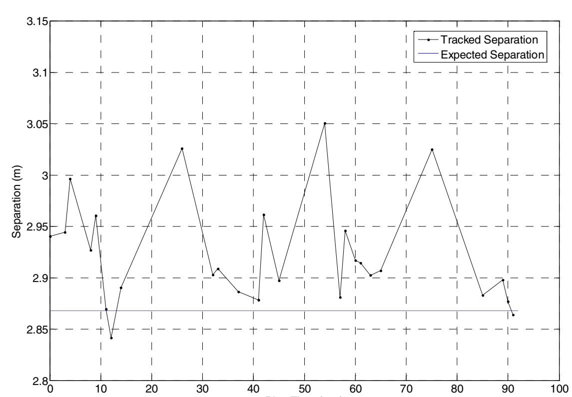

Figure 7. Tracking accuracy, 3-D separation, WHOI navigation ping.

Acoustic receiver and transmitter software used in the topside tracking system is currently being adapted to a PC/104 platform. This effort is being performed at ARD, and is funded by the Submarine Acoustic Silencing Maintenance Program (SASMP). PC/104 boards have a small form factor, suitable for many AUVs. The University of Idaho is in a unique position to leverage this effort and plans to evaluate this technology for possible use on an AUV.

Diagnostic work and corrective measures are needed to resolve a known multipath issue in the current tracking system. One or more tracking nodes may be tilted at unacceptable angles. The suspected cause is a cabling malfunction, which prevents the nodes from righting themselves properly. Options are being considered to verify and correct this problem. Acoustic beam-pattern testing which is being performed on the nodes under development will ensure the same problems do not transfer to the new tracking range.

ACKNOWLEDGMENT

The authors gratefully acknowledge the support of the Office of Naval Research, through “Electromagnetic Signature Assessment System Using Multiple Autonomous Underwater Vehicles (AUVs)”, ONR N00014-08-1-0779.

Special thanks to the ARD team, including; Craig Nielsen, Keith Hertel, Jeanne Hom, Masha Ritzheimer, Vickie Pfeifer, Tom Tupper, Jim Baxter, Pat Molvik, Denny Spencer, and many others who supported this effort.

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