

Recent Advances in Synchronous-Clock One-Way-Travel-Time Acoustic Navigation

Ryan M. Eustice*, Louis L. Whitcomb†, Hanumant Singh‡, and Matthew Grund‡

*Department of Naval Architecture & Marine Engineering
University of Michigan, Ann Arbor, MI 48109
Email: eustice@umich.edu

†Department of Mechanical Engineering
Johns Hopkins University, Baltimore, MD 21218
Email: llw@jhu.edu

‡Department of Applied Ocean Physics & Engineering
Woods Hole Oceanographic Institution, Woods Hole, MA 02543
Email: {hanu,mgrund}@whoi.edu

Abstract— This paper reports recent results in the development and deployment of a synchronous-clock acoustic navigation system suitable for the simultaneous navigation of multiple underwater vehicles. The goal of this work is to enable the task of navigating multiple autonomous underwater vehicles (AUVs) over length scales of $\mathcal{O}(100 \text{ km})$, while maintaining error tolerances commensurate with conventional long-baseline transponder-based navigation systems ($\mathcal{O}(1 \text{ m})$), but without the requisite need for deploying, calibrating, and recovering seafloor anchored acoustic transponders. Our navigation system is comprised of an acoustic modem-based communication/navigation system that allows for onboard navigational data to be broadcast as a data packet by a source node, and for all passively receiving nodes to be able to decode the data packet to obtain a one-way travel time pseudo-range measurement and ephemeris data. We present field results for a two-node configuration consisting of a surface ship acting as a global navigation aid to a Doppler-aided AUV.

I. INTRODUCTION

Few techniques presently exist for reliable three-dimensional position sensing for underwater vehicles. Depth, altitude, heading, and roll/pitch attitude can all be instrumented with high bandwidth internal sensors, however, XY position, in contrast, remains difficult to instrument and is normally measured acoustically in oceanographic and commercial applications.

Conventional long-baseline (LBL) acoustic navigation systems require multiple fixed transponders — i.e., fixed or moored on the seafloor [1], [2], on the hull of a surface ship [3], or on sea-ice [4]. With a maximum acoustic range of 5–10 km, fixed LBL networks can cover only limited mission areas. Moreover, existing LBL navigation systems are designed to navigate one vehicle per interrogation-response acoustic cycle. This is acceptable for single vehicle deployments, but less desirable for multi-vehicle deployments because the interrogation-response navigation update period

increases linearly with the number of vehicles (thereby proportionally decreasing each vehicle’s overall navigation update rate). The result is unacceptably low LBL navigation update rates. The existing prevalence of LBL systems within the oceanographic community is due to a lacuna of other means for obtaining bounded-error sub-sea XY position.

While the advent of the global positioning system (GPS) has ushered in a new revolution in bounded-error terrestrial navigation for both surface and air vehicles, seawater is opaque to the radio-frequencies upon which GPS relies and, thus, GPS cannot be used by submerged underwater vehicles. Though ultra-short-baseline (USBL) acoustic navigation systems are preferred for short-range navigation, they are of limited usefulness for long-range navigation [5], [6].

The high cost and power consumption of inertial navigation systems has, until now, precluded their widespread use in non-military undersea vehicles. Compact, low-cost, low-power inertial navigation system (INS) systems have recently become commercially available, offering an alternative method for instrumenting absolute XYZ displacement [7], [8]. Modern INS position error is on the order of 1% of path-length, hence, INS alone is inadequate to support the needs of long-range bounded-error navigation. For example, the path length of a vehicle traveling 3 knots for 48 hours is 144 nm (266 km), resulting in an INS position error of 1.4 nm (2.6 km), which is unacceptably large. For a survey of current underwater navigation technologies, the reader is referred to [9].

In this paper we pursue the development of a synchronous-clock modem-based navigation system capable of supporting multi-vehicle bounded-error navigation over unprecedented length scales (e.g., $\mathcal{O}(100 \text{ km})$). Our navigation framework employs WHOI Micro-Modems [10]–[12], an underwater acoustic modem developed by Woods Hole Oceanographic Institution (WHOI), in conjunction with commercial off-the-shelf (COTS) low-power stable clocks to yield a navigation

system capable of inter-vehicle communication and one-way travel time (OWTT) ranging. Previous work using modems and synchronous-clock navigation has been reported in [13] for autonomous surface-craft; in that work each vehicle was equipped with a GPS receiver to provide a common timebase for synchronous ranging. Synchronous-pinger OWTT navigation was reported in [14] where integrated range-rate positioning was used for AUV docking using an early predecessor of the modern WHOI Micro-Modem. Non-modem synchronous-clock OWTT ranging has been reported in [2] for “in-hull navigation” of the manned deep-submergence vehicle Alvin. Other loosely related work involving single transponder two-way travel-time (TWTT) navigation has been reported in [15]–[21].

The rest of the paper is organized as follows. Section II describes our synchronous-clock implementation and methodology. Section III presents a weighted sensor fusion framework for combining OWTT pseudo-range measurements with strap-down onboard vehicle odometry for bounded-error navigation. Section IV reports for a set of data collected in-situ by a bottom-lock Doppler-aided AUV accompanied with OWTT pseudo-range measurements acquired from a GPS-equipped surface ship. Finally, section V closes with some concluding remarks.

II. SYNCHRONOUS-CLOCK ACOUSTIC NAVIGATION

Most acoustic navigation systems are based upon measuring two-way time-of-flight (TOF) ranges whereby the navigation cycle consists of a vehicle-initiated interrogation pulse followed by a reply from all passively listening transponders [2], [3]. In these systems, *each* node (i.e., vehicle) in the acoustic network must interrogate the network in order to obtain a two-way TOF measurement between it and all replying nodes. The advantage of such a system is that no absolute precision-clock is required for TOF measurement, however, the disadvantage is that in a N vehicle environment the overall update rate for each vehicle *decreases* as $\frac{1}{N}$.

Accurate OWTT ranging can be determined by precisely knowing the transmit and receive times of an underwater acoustic communications packet. The result is a direct one-way TOF measurement from source to receiver. The advantage over TWTT ranging is that OWTT ranging readily scales to a multi-vehicle environment within a master/slave architecture. This is because when a source (master) node interrogates the network, all receiving nodes (slaves) can *passively* measure the one-way TOF between each of them and the source node. Hence, in a N vehicle environment, the overall update rate for each vehicle remains constant. The disadvantage, however, is increased complexity in hardware design since all nodes must carry their own synchronized, stable precision-clock.

A. Methodology

Our methodology is to use OWTT ranging capabilities in the context of a surface-ship acting as a moving transponder. For this purpose, we are employing the synchronous-transmission capabilities of the WHOI Micro-modem [10]–

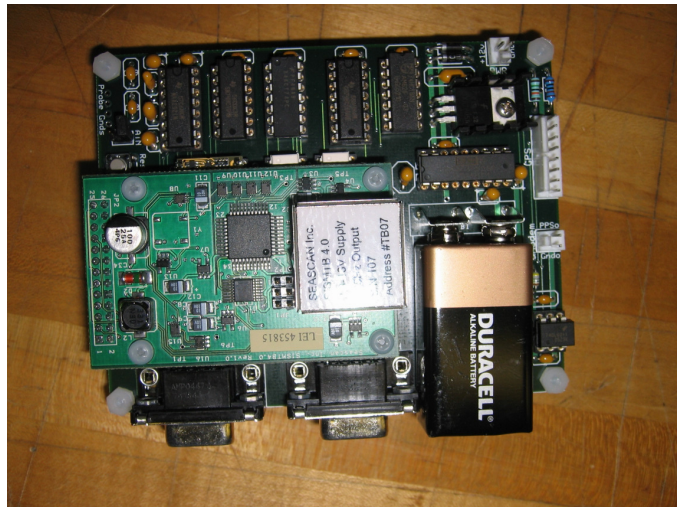


Fig. 1. A depiction of the PPSBOARD designed by the authors. The PPSBOARD integrates a COTS TXCO with a micro-controller based PCB. The PPSBOARD allows for higher-level clock functionality such as PPS synchronization control, measuring of pre and post dive TXCO PPS drift, and generating output suitable for RTC stabilization on the host PC via the open-source NTP algorithm.

[12]. The synchronous-transmission feature of the WHOI Micro-modem allows it to directly and accurately measure time-of-arrival (TOA) to within $125 \mu\text{s}$ (i.e., 18.75 cm at 1500 m/s) between a source and receiver using a user supplied external pulse per second (PPS) reference. This common timebase allows for a synchronous modem communication/navigation system whereby navigation data packets can encode time of origin information as well as local ephemeris data (e.g., x, y, z positional data and error metric). Navigation packets can be broadcast to the network, allowing all receiving nodes to passively measure the elapsed TOF between source node and destination. The OWTT pseudo-range knowledge, when used in conjunction with the decoded ephemeris data and other onboard vehicle navigation data, provides a mechanism for bounded-error self-localization.

In our method, a ship maneuvers with an AUV fleet, tending to vehicle launch/recovery support, while also acting as a global navigation aid by broadcasting GPS-derived ship-transducer position to the vehicle network. All vehicles which are within listening range of the ship and which passively receive the GPS ephemeris can then use this knowledge to compute a running position fix and correct accumulated dead-reckon error. For this purpose, we anticipate that vehicles will be instrumented with a standard suite of oceanographic navigation sensors including pressure depth, attitude, Doppler velocity log (DVL), and possibly an INS.

B. Implementation

In our system, each submerged node is equipped with a COTS low-power (10 mW) temperature compensated crystal oscillator (TXCO) manufactured by SeaScan Inc. This free-running TXCO is capable of providing a 0.02 ppm (typical) (i.e., a drift-rate of about 1 ms per 14 h) reference pulse at the

rate of 1 PPS. This translates into a maximum per-dive drift-induced range-error of 1.5 m, which is commensurate with standard 12 kHz LBL. The TXCO is naturally free-running, therefore, we designed a micro-controller based printed circuit board (PCB) daughter card, called a PPSBOARD, to provide higher-level clock functionality (Fig. 1).

The PPSBOARD mates to the TXCO and controls synchronization of the TXCO’s PPS to an absolute reference clock as well as measures the TXCO’s PPS offset with respect to this reference. This capability allows us to synchronize the TXCO to a common timebase at the beginning of a mission while on the surface, such a GPS-derived Coordinate Universal Time (UTC), and then measure the pre and post dive drift of the TXCO, which is useful for modeling clock drift. Additionally, the PPSBOARD generates a NTP-compliant string and waveform that can be used to keep real-time clock (RTC) drift onboard the vehicle host PC to within sub-milliseconds of absolute time [22]. This level of accuracy is sufficient for the host PC to be able to assign which second corresponds to which TXCO PPS pulse when communicating with the Micro-Modem. This time reference is then embedded as the time of origin in the acoustic navigation packet.

The surface ship uses a COTS GPS-based network time-server for a stable clock source. The unit, manufactured by Meinberg Inc., uses a high-quality oven compensated crystal oscillator (OXCO) with a GPS-synchronous accuracy of 1E-6 ppm and a free-running accuracy of 5E-4 ppm. Hence, the ship-based timeserver can be considered essentially drift-free and only the vehicle TXCO drift must be accounted for when computing pseudo-range measurements from TOF data.

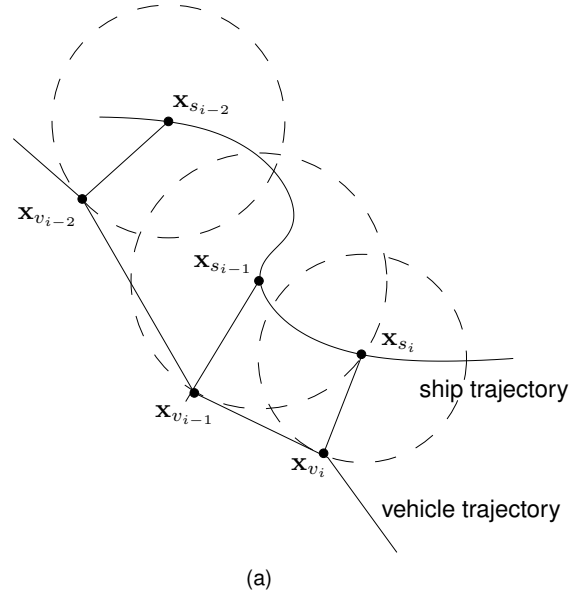
III. FUSION FRAMEWORK

In this section, we describe a nonlinear weighted least-squares framework for bounded-error XY vehicle navigation that combines: 1) vehicle-derived inter-ping odometry, 2) ship GPS-derived position, and 3) OWTT pseudo-range measurements between ship and vehicle. The framework is suitable for offline batch post-processing for the purposes of optimal re-navigation, and can also be extended to vehicle in-situ online use by selecting an appropriate sliding time window of most recent data.

A. Assumptions

In the forthcoming formulation we make the following assumptions:

- First, that dives are relatively short in length (i.e., on the order of several hours) such that PPS drift-induced range-bias remains negligible over the course of the dive and, therefore, can be neglected.
- Second, that the sound speed profile is locally homogeneous within the prescribed bounding box of vehicle operations. This implies that TOF measurements can be converted to pseudo-ranges via a constant scaling by sound velocity.
- Third, that the estimation problem can be reduced to that of XY horizontal plane dynamics only. For this purpose,



Measurement Origin	Observation Model
OWTT Pseudo-Range	$z_{r_i} = \ \mathbf{x}_{v_i} - \mathbf{x}_{s_i}\ + w_{r_i}$
Ship GPS Position	$z_{g_i} = \mathbf{x}_{s_i} + \mathbf{w}_{g_i}$
Vehicle Odometry	$z_{o_i} = (\mathbf{x}_{v_i} - \mathbf{x}_{v_{i-1}}) + \mathbf{w}_{o_i}$

Fig. 2. OWTT navigation. (a) A depiction of the 2D OWTT range geometry where \mathbf{x}_{s_i} and \mathbf{x}_{v_i} denote corresponding samples from the ship and vehicle trajectories, respectively. (b) A table of the available measurements and their relation to state entries. The w_{r_i} , \mathbf{w}_{g_i} , and \mathbf{w}_{o_i} terms each represent additive measurement noise.

we assume that the vehicle is equipped with a pressure depth sensor of sufficient accuracy such that slant-range pseudo-ranges can be projected onto the horizontal plane. This also requires that the ship’s trajectory never pass directly over top the vehicle, which would otherwise introduce a singularity into the horizontal range projection.

- Fourth, that the vehicle is capable of measuring its own dead-reckoned (DR) XY odometry in-between OWTT pings and associated measurement covariance. For example, this could be obtained from bottom-lock Doppler velocity data, an onboard INS system, or a vehicle dynamic model.
- Finally, in the current formulation, we assume that all OWTT pseudo-range measurements occur between surface ship and vehicle only. At present, we do not consider inter-vehicle OWTT ranging. Hence, it is sufficient that each vehicle only track ship trajectory for the purposes of self-localization.

B. State Description

We denote topside ship trajectory as $\mathbf{x}_s(t) = [x_s(t), y_s(t)]^\top$, where $(x_s(t), y_s(t))$ represents XY ship transducer position in a locally-defined Cartesian coordinate frame (e.g., Universal Transverse Mercator (UTM) System coordinates). Similarly, we denote bottomside vehicle

trajectory as $\mathbf{x}_v(t) = [x_v(t), y_v(t)]^\top$. In the aforementioned scenario, the ship initiates a OWTT broadcast at time t_s while the vehicle receives that same broadcast at a corresponding latter time $t_v > t_s$. For a given OWTT range measurement, z_{r_i} , indexed by subscript i , we note that this measurement actually corresponds to a ship/vehicle sample pair, \mathbf{x}_{s_i} and \mathbf{x}_{v_i} , each sampled at distinct times $\mathbf{x}_{s_i} = \mathbf{x}_s(t_{s_i})$ and $\mathbf{x}_{v_i} = \mathbf{x}_v(t_{v_i})$, respectively. For notational convenience, we drop the explicit dependence on time and instead implicitly embed sample time within the \mathbf{x}_{s_i} and \mathbf{x}_{v_i} sample index notation. Fig. 2 depicts a sequence of OWTT pseudo-range measurements occurring between ship and vehicle along with the available measurement observation models.

C. Weighted Optimization

Under the assumed observation models of ship GPS position, vehicle-derived inter-ping odometry, and OWTT pseudo-ranging, we can write our weighted least-squares objective function, $C(\mathbf{X})$, as

$$\begin{aligned}
C(\mathbf{X}) = & \\
& \frac{1}{2} \sum_{i=0}^{n-1} (z_{r_i} - \|\mathbf{x}_{v_i} - \mathbf{x}_{s_i}\|)^\top \Sigma_{r_i}^{-1} (z_{r_i} - \|\mathbf{x}_{v_i} - \mathbf{x}_{s_i}\|) \\
& + \frac{1}{2} \sum_{i=0}^{n-1} (\mathbf{z}_{g_i} - \mathbf{x}_{s_i})^\top \Sigma_{g_i}^{-1} (\mathbf{z}_{g_i} - \mathbf{x}_{s_i}) \\
& + \frac{1}{2} \sum_{i=1}^{n-1} (\mathbf{z}_{o_i} - (\mathbf{x}_{v_i} - \mathbf{x}_{v_{i-1}}))^\top \Sigma_{o_i}^{-1} (\mathbf{z}_{o_i} - (\mathbf{x}_{v_i} - \mathbf{x}_{v_{i-1}})),
\end{aligned} \tag{1}$$

where Σ_{r_i} , Σ_{g_i} , and Σ_{o_i} are the individual relative measurement weights. To solve, we employ the Levenberg-Marquardt algorithm [23] starting with an initial guess of dead-reckoned vehicle position and GPS-measured ship position.

IV. RESULTS

In this section we report results for a set of field experiments employing OWTT navigation. The experiment was for a two-node configuration consisting of a surface ship and single submerged AUV. For this experiment, we used the WHOI SeaBED AUV platform (Fig. 3).

A. Experimental Setup

SeaBED is instrumented with a typical suite of oceanographic navigation sensors including pressure sensor depth, 1200 kHz DVL, an IXSEA North-seeking 3-axis fiber optic gyro for attitude, and a PPS-capable WHOI Micro-modem. In addition, we integrated our PPSBOARD and a Garmin GPS-16HVS GPS receiver into the vehicle so that we could conduct OWTT experiments. The Garmin GPS unit outputs a 1 PPS reference signal accurate to within 1 μ s of UTC when it has GPS lock. We use this PPS reference for pre-dive time synchronization of the free running TXCO onboard the AUV while at the surface.

The surface ship is equipped a PPS-capable Micro-modem, a GPS receiver used for measuring ship transducer position,

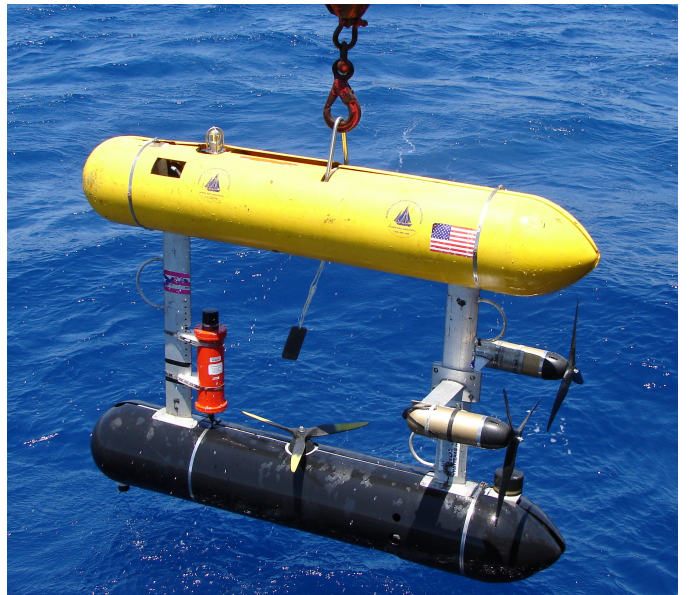


Fig. 3. The SeaBED AUV as used during field experiments. The orange LinkQuest Tracklink beacon mounted on the front strut provided an independent measurement of ship-to-vehicle range.

and a Meinberg GPS-based NTP time server as a stable clock reference. The Meinberg unit outputs a 1 PPS signal accurate to within 100 ns and is drift free.

B. Experimental Results

During December of 2005, we operated the SeaBED AUV offshore from the coast of Woods Hole, MA while aboard the R/V Tioga. For this set of experiments we deployed the AUV in approximately 15 m of water and programed the vehicle to swim two 100 m concentric boxes at a forward speed of 0.4 m/s. In this environment, the AUV had Doppler bottom-lock from the surface with a total mission time of approximately 1.5 hours; PPS clock-drift onboard the vehicle was less than 4 μ s (Fig. 5). The ship remained on anchor and OWTT ranges were broadcast at a periodic schedule of every 5 then 20 seconds. Fig. 4 displays the raw OWTT data recorded between the AUV and ship; for comparison, independently measured TWTT (Tracklink USBL) ranges are shown.

Fig. 6 displays results from the weighted nonlinear least-squares fusion of the OWTT pseudo-ranges and bottom-lock DVL odometry. The raw DVL trajectory, shown in blue, was obtained by forward Euler integration, using the GPS drop-position of the AUV as the origin. Shown in red is the globally referenced OWTT derived trajectory; this result was post-processed offline. Shown in green is the independently measured post-dive GPS position of the AUV, which cross-validates the OWTT result. Fig. 6(b) provides a plot of GPS referenced error versus time, showing good agreement between OWTT derived position and onboard GPS.

V. CONCLUSIONS

This paper described recent advances in the development of a synchronous-clock acoustic communication/navigation sys-

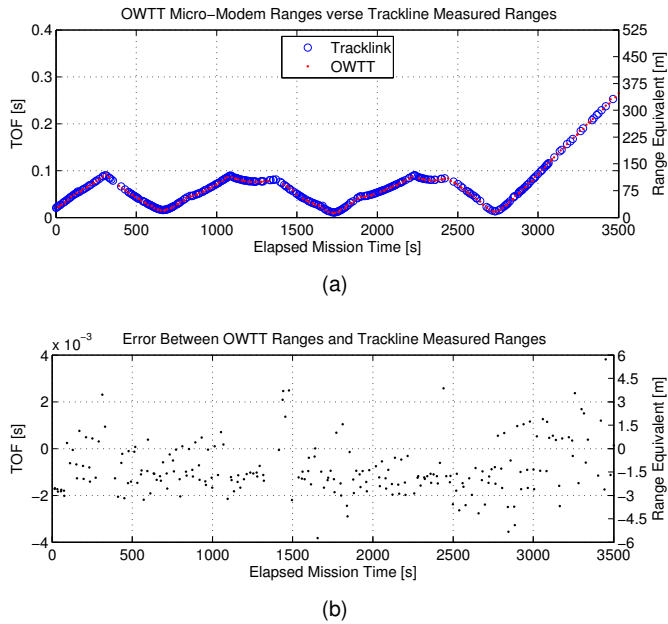


Fig. 4. A comparison of modem-derived OWTT ranges versus USBL TWTT ranges, as measured between surface ship and AUV. (a) A plot of raw ranges as measured by the the LinkQuest Tracklink system and modem-derived OWTTs. (b) A comparison of the TOF discrepancy obtained by linearly interpolating the USBL range data to the OWTT timebase. For reference, the y-axis scale on the right shows the equivalent range error assuming a sound speed of 1500 m/s.

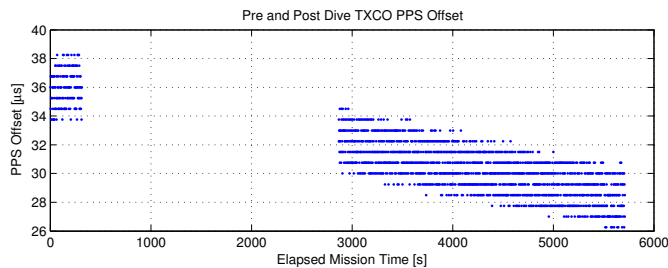


Fig. 5. Pre and post-dive measured TXCO PPS offset with respect to GPS-derived absolute PPS timebase. During the course of the dive, the TXCO drifted by approximately 4 μ s from an initial offset of 36 μ s to 32 μ s.

tem for underwater vehicles. The long-term goal of this work is to enable the task of navigating a fleet of AUVs over order 100 km length scales with bounded-error commensurate with standard 12 kHz LBL navigation. Toward that end, we have reported the development of a low power, stable clock system suitable for integration on AUVs. We have also established a preliminary nonlinear least-squares fusion framework for combining OWTT pseudo-range measurements with vehicle-odometry for bounded-error navigation. Results from a field experiment validating OWTT navigation were reported. Future research in this area will address the modeling of PPS clock drift, the use of water-lock DVL velocity odometry, and a decentralized, recursive estimation framework to support multi-vehicle navigation with inter-vehicle ranging.

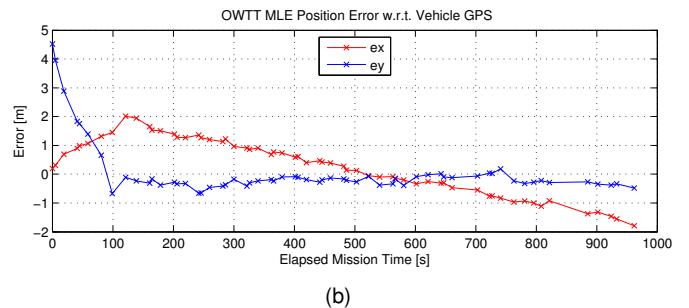
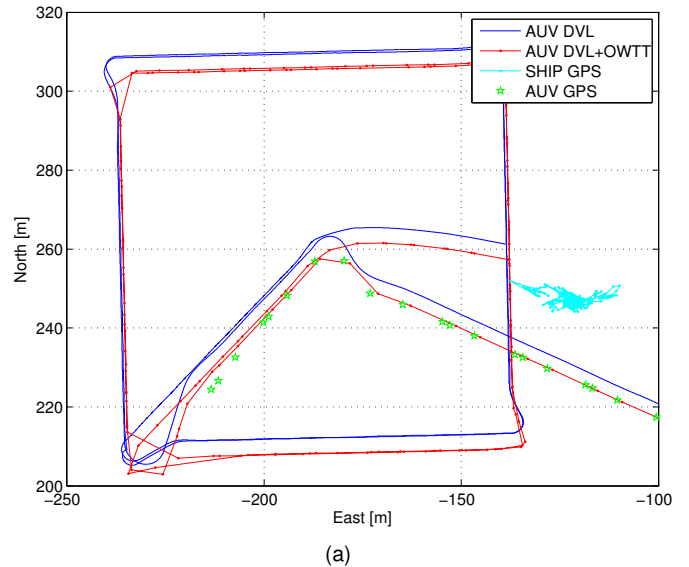


Fig. 6. Results for a two node network consisting of a bottom-lock Doppler-aided AUV and a GPS-equipped surface ship. Each node is equipped with a WHOI Micro-Modem and onboard stable PPS source for synchronous clock communication/navigation. (a) The AUV swam two co-located box trajectories (100 m per side), each at a different depth set-point while the ship remained anchored. Shown in blue is the raw DVL-derived AUV trajectory; in cyan is the GPS-derived ship position; in red is the globally referenced MLE AUV trajectory; and in green is the end-of-dive GPS-measured AUV position, which serves as an independent ground-truth. (b) Shown here are the XY components of error between OWTT-derived and GPS-measured AUV position while on the surface. This segment of data is from the last 15 minutes of the mission; prior to that the vehicle had been submerged for close to 75 minutes.

VI. ACKNOWLEDGMENTS

This work was supported by the National Science Foundation under NSF Award Numbers ATM-0427220 and ATM-0428122.

REFERENCES

- [1] L. Whitcomb, D. Yoerger, and H. Singh, "Towards precision robotic maneuvering, survey and manipulation in unstructured undersea environments," in *Proc. Intl. Symp. Robotics Research*, Springer Verlag, London, 1998, pp. 45–54.
- [2] M. Hunt, W. Marquet, D. Moller, K. Peal, W. Smith, and R. Spindel, "An acoustic navigation system," Woods Hole Oceanographic Institution, Tech. Rep. WHOI-74-6, Dec. 1974.
- [3] P. Milne, *Underwater acoustic positioning systems*. Houston: Gulf Publishing Company, 1983.
- [4] J. Bellingham, M. Deffenbaugh, J. Leonard, and J. Catipovic, "Arctic under-ice survey operations," *Unmanned Systems*, vol. 12, pp. 24–29, 1994.

- [5] H. Singh, J. Catipovic, R. Eastwood, L. Freitag, H. Henriksen, F. Hover, D. Yoerger, J. Bellingham, and B. Moran, "An integrated approach to multiple AUV communications, navigation and docking," in *Proc. IEEE/MTS OCEANS Conf. Exhib.*, vol. 1, Fort Lauderdale, Sept. 1996, pp. 59–64.
- [6] S. Smith and D. Kronen, "Experimental results of an inexpensive short baseline acoustic positioning system for AUV navigation," in *Proc. IEEE/MTS OCEANS Conf. Exhib.*, vol. 1, Halifax, NS, 1997, pp. 714–720.
- [7] M. Larsen, "High performance Doppler-inertial navigation-experimental results," in *Proc. IEEE/MTS OCEANS Conf. Exhib.*, vol. 2, Providence, RI, 2000, pp. 1449–1456.
- [8] T. Gaiffe, "U-Phins: a FOG-based inertial navigation system developed specifically for AUV navigation and control," in *Intl. Conf. Underwater Intervention*, New Orleans, LA, Feb. 2002.
- [9] J. Kinsey, R. Eustice, and L. Whitcomb, "Underwater vehicle navigation: recent advances and new challenges," in *IFAC Conf. on Manoeuvring and Control of Marine Craft*, Lisbon, Portugal, Sept. 2006, Accepted, To Appear.
- [10] L. Freitag, M. Grund, S. Singh, J. Partan, P. Koski, and K. Ball, "The WHOI micro-modem: an acoustic communications and navigation system for multiple platforms," in *Proc. IEEE/MTS OCEANS Conf. Exhib.*, Washington, D.C., Sept. 2005.
- [11] L. Freitag, M. Grund, J. Partan, K. Ball, S. Singh, and P. Koski, "Multi-band acoustic modem for the communications and navigation aid AUV," in *Proc. IEEE/MTS OCEANS Conf. Exhib.*, Washington, D.C., Sept. 2005.
- [12] S. Singh, M. Grund, B. Bingham, R. Eustice, H. Singh, and L. Freitag, "Underwater acoustic navigation with the WHOI micro-modem," in *Proc. IEEE/MTS OCEANS Conf. Exhib.*, Boston, MA, Sept. 2006, Accepted, To Appear.
- [13] J. Curcio, J. Leonard, J. Vaganay, A. Patrikalakis, A. Bahr, D. Battle, H. Schmidt, and M. Grund, "Experiments in moving baseline navigation using autonomous surface craft," in *Proc. IEEE/MTS OCEANS Conf. Exhib.*, Washington, D.C., Sept. 2005.
- [14] H. Singh, J. Bellingham, F. Hover, S. Lerner, B. Moran, K. von der Heydt, and D. Yoerger, "Docking for an autonomous ocean sampling network," *IEEE J. Oceanic Eng.*, vol. 26, no. 4, pp. 498–514, Oct. 2001.
- [15] A. Scherbatyuk, "The AUV positioning using ranges from one transponder LBL," in *Proc. IEEE/MTS OCEANS Conf. Exhib.*, vol. 3, San Diego, CA, 1995, pp. 1620–1623.
- [16] M. Larsen, "Synthetic long baseline navigation of underwater vehicles," in *Proc. IEEE/MTS OCEANS Conf. Exhib.*, vol. 3, Sept. 2000, pp. 2043–2050.
- [17] J. Vaganay, P. Baccou, and B. Jouvencel, "Homing by acoustic ranging to a single beacon," in *Proc. IEEE/MTS OCEANS Conf. Exhib.*, vol. 2, Sept. 2000, pp. 1457–1462.
- [18] P. Baccou and B. Jouvencel, "Homing and navigation using one transponder for AUV, postprocessing comparisons results with long base-line navigation," in *Proc. IEEE Intl. Conf. Robot. Auto.*, vol. 4, 2002, pp. 4004–4009.
- [19] A. Gadre and D. Stilwell, "Toward underwater navigation based on range measurements from a single location," in *Proc. IEEE Intl. Conf. Robot. Auto.*, vol. 5, 2004, pp. 4472–4477.
- [20] —, "A complete solution to underwater navigation in the presence of unknown currents based on range measurements from a single location," in *Proc. IEEE/RSJ Intl. Conf. Intell. Robots Systems*, 2005, pp. 1420–1425.
- [21] A. Ross and J. Jouffroy, "Remarks on the observability of single beacon underwater navigation," in *Proc. Intl. Symp. Unmanned Unteth. Subm. Tech.*, Aug. 2005.
- [22] D. Mills, "Network time protocol version 4 reference and implementation guide," University of Delaware, Tech. Rep. 06-06-1, June 2006.
- [23] W. Press, S. Teukolsky, W. Vetterling, and B. Flannery, *Numerical recipes in C: the art of scientific computing*, 2nd ed. Cambridge University Press, 1992.