# A long term vision for long-range ship-free deep ocean operations: persistent presence through coordination of Autonomous Surface Vehicles and Autonomous Underwater Vehicles

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***Abstract*—We outline a vision for persistent and/or long-range seafloor exploration and monitoring utilizing autonomous surface vessels (ASVs) and autonomous underwater vehicles (AUVs) to conduct coordinated autonomous surveys. Three types of surveys are envisioned: a) Autonomous tending of deep-diving AUVs: deployed from a research vessel, the ASV would act as a force-multiplier, watching over the AUV to provide operators and scientists with real-time data and re-tasking capabilities, while freeing the ship to conduct other over-the-side operations; b) Ridge-segment-scale (100 km) autonomous hydrothermal exploration: combined with conventional gliders or long-endurance AUVs, an ASV could tend a fleet of underwater assets equipped with low-power chemical sensors for mapping hydrothermal plumes and locating seafloor hydrothermal venting. Operators would control the system via satellite, such that a support ship would be needed only for initial deployment and final recovery 1-2 months later; and c) Basin-scale (10,000 km) autonomous surveys: a purpose-built autonomous surface vessel (mother-ship) with abilities up to and including autonomous deployment, recovery, and re-charge of subsea robots could explore or monitor the ocean and seafloor on the oceanic basin scale at a fraction of the cost of a global-class research vessel. In this paper we outline our long term conceptual vision, discuss some preliminary enabling technology developments that we have already achieved and set out a road-map for progress anticipated over the next 2-3 years. We present an overview of the system architecture for autonomous tending along with some preliminary field work.***

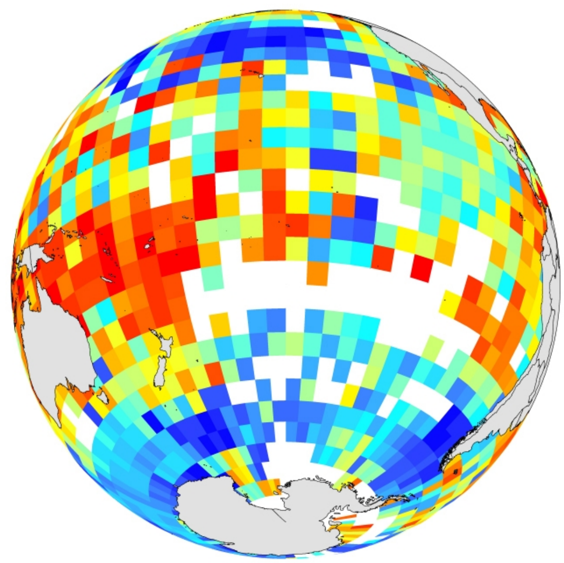

Fig. 2. HFI* map (www.coml.org) showing how biodiversity hot-spots to West and East in the South Pacific are separated by areas devoid of data. *HFI: Hurlbert's First Index is a sample-size independent proxy for species richness. Here, colours (red = high) show predicted numbers of distinct species in a random sample of 50 observations; white: areas still awaiting collection of 50+ observations.

## I. Introduction

Half our planet is covered by deep ocean more than 3000m deep and most of it remains unexplored. For example, the South Pacific basin represents Earth's largest deep ocean basin and the largest contiguous ecosystem for life on our planet, with a broad spectrum of habitats (Fig. 1), yet we know very little of what lives in its trenches, across its abyssal plains, around seamounts and along its mid-ocean ridges [1]. Where we have begun to explore and document, around the Ocean Margins, what has been established are that the South Pacific hosts biodiversity and evolutionary hotspots to both West and East (Fig. 2) yet vast expanses of the open ocean lack sufficient data to allow characterization, in between these hotspots [1]. From a different perspective, more than 30 years after the discovery of venting, more than 80% of the world's ridge crests remain completely unexplored for hydrothermal activity [2]. Following an international InterRidge workshop held in June 2010, UK, it was recommended that coordinated investigation of the South Atlantic become an immediate priority (Fig. 3), not least because a similar investigation of the South Pacific would requires a much greater burden of shiptime, following established exploration methodologies, and in at least some latitudes require a new technological approach [3].

Over the past decade, autonomous underwater vehicles (AUVs) have played increasingly important roles in seafloor studies in the deep ocean but the presence of a support ship

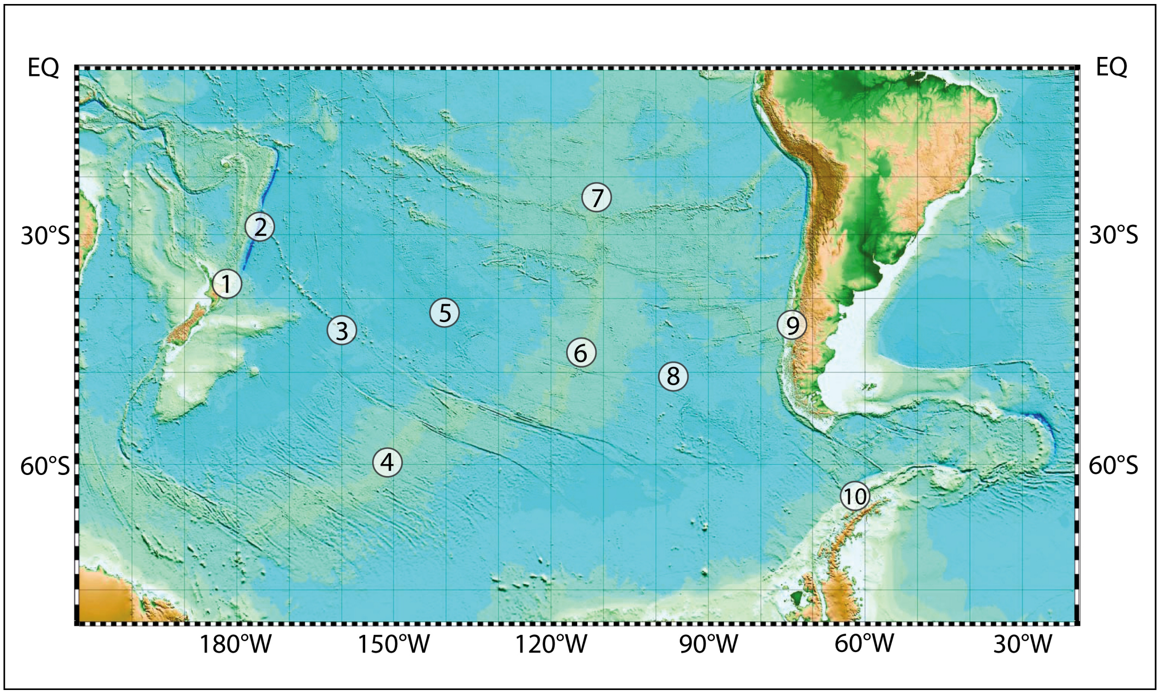


Fig. 1. Bathymetric projection of the South Pacific Ocean (reproduced from German et al., 2011) with numbered field locations: 1, Tonga-Kermadec arc; 2, deep-ocean trenches; (3) mid-plate seamounts of the Louisville Ridge; 4 & 6, Pacific-Antarctic Ridge; 5 & 8, abyssal plains; 7, Southern EPR; 9, Chile margin; 10, Bransfield Strait back-arc basin.

and the concomitant expense of ship-time ($20k-$50k/day) has favored the development of relatively fast, power-hungry imaging vehicles designed to return gigabytes of acoustic or optical imagery over deployments lasting hours to a few days. Elimination of the support ship would fundamentally alter the scale of achievable AUV missions by removing the penalty associated with the cost of ship time. Free to move slowly and thereby burn less energy per unit distance traveled, AUVs with low-power or intermittent sensing payloads can achieve endurance of many months and ranges of 1000s of km [4], [5]. This represents a potentially transformative technology for basin-scale studies of the deep ocean floor. Unattended AUV operations would enable low-cost chemical mapping for hydrothermal vent detection and the generation of high resolution magnetic and gravimetric maps at a scale relevant to segment-scale geological processes. Targeted seafloor photographs taken periodically in response to particular triggers or remote retasking by operators would permit preliminary biogeographical characterization of vent, seep, and seamount fauna. To take full advantage of these emerging capabilities, we are pursuing the demonstration of enabling aspects of a two-body robotic near-seafloor survey system for very long range (1000s of km) surveys of the deep ocean, independent of a support ship.

## II. Long-Term Vision for Ship-Free Deep Ocean Operations

Our long-term (decadal) vision for ship-free deep ocean operations spans three phases of increasing complexity. We believe the first is immediately accessible and the second will be achievable in the next 2-3 years. All three phases are illustrated in Fig.4.

### A. Phase I — Autonomous Tending

First, we envisage that autonomous tending of an existing AUV such as the Sentry vehicle with which our group is most familiar would act as an immediate force-multiplier for operations of a kind that are already commonplace among the deep ocean AUV community. Currently, an AUV deployed to depth can only be tracked and the status of its mission can only be monitored if the support ship remains within USBL range. This is also required if any re-tasking of the vehicle is to be effected based on results collected within the lifetime of any given dive. By deploying an ASV as well as the AUV from the support ship, several of the roles that require the ship to remain within USBL range of the AUV can be eliminated. First, the ASV can provide continuous GPS tracking of its own location which, coupled with acoustic communications, can provide updated navigational information to the AUV at depth beyond what the AUV can achieve on its own (relying on, for example, some combination of Inertial Navigation and Doppler Velocity Logging). Second, the ASV can also serve as a communication relay beacon to the support ship which can, hence, conduct over the horizon operations while the ASV provides real-time updates on the status of the mission including an ability to alert the mother ship if the mission reaches a premature end and the vehicle is returning to the surface for recovery. A final important operation that the presence of an ASV in this attending mode would facilitate is the ability not only to relay data-packets from the seafloor to the mission team aboard ship,

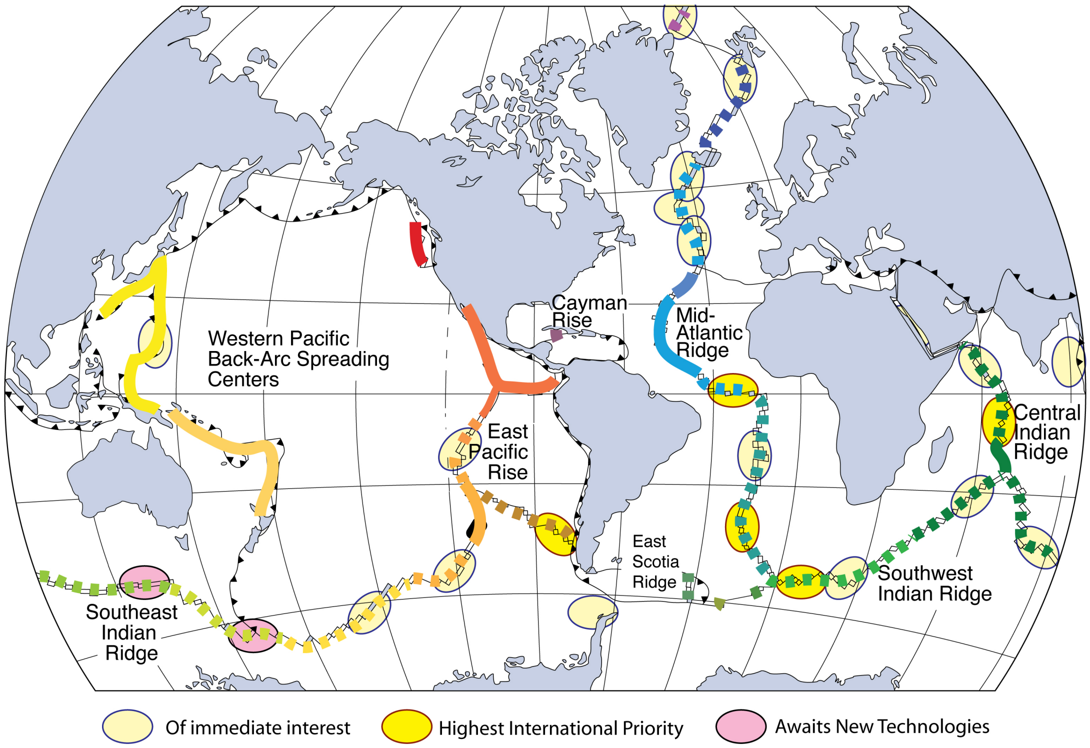


Fig. 3. Annotated map (reproduced from German et al., 2011) of the global ridge crest, illustrating a model of the biogeographic differentiation of invertebrate species associated with hydrothermal vents and regions recently identified by InterRidge as being of continuing importance for future ridge-crest exploration [3]. Ellipses show three categories of importance assigned to twenty three separate locations distributed along the ridge axis; different coloured lines along-axis represent regions that share many of the same species (see [6]).

but also to allow operations teams aboard that ship to analyse those data and to retask the AUV at depth, as required, without breaking off whatever other over the horizon operations the support ship may be engaged in at that time. In this mode, the support ship would still be required to be present for all launch and recovery operations on timescales with a repeat cycle of one or more days.

### *B. Phase II — Ridge-Segment Scale Autonomous Exploration*

At the second level, we envisage a fleet of longer-range vehicles (e.g. gliders) that could be deployed and coordinated in their exploration over hundreds of kilometres. A good pilot test-case for this might be in exploration for new sites of hydrothermal activity along previously unstudied sections of the global Mid-Ocean Ridge-crest as called for recently by the InterRidge Long Range Exploration workshop [3]. In such a case, ship operations would be required for initial deployment (and subsequent recovery) of the vehicle fleet but the ASV would provide the primary source of geo-referenced navigation using synchronized one way travel times [7], [8] and they might be to enable multiple vehicle operations at depth to be coordinated from a single surface vehicle. This same ASV would then also serve as an essential link to relay data to a shore-based team managing the glider fleet and also to relay any retasking of missions required for any one or more of the vehicles at such time as any one at-depth vehicle intercepts hydrothermal plume signatures. Apart from the initial deployment and the final recovery of the ASV and glider fleet, no surface ship assets should be required throughout any such deployment.

### *C. Phase III — Oceanic Basin-Scale Autonomous Exploration and Monitoring*

Finally, for the longer term, we envisage next generation long-range AUVs (e.g., [4], [5]) that could be deployed from more substantive and highly capable ASVs, beyond the current state of the art, that could also conduct autonomous deployment, recharging and recovery of AUVs. Such vehicles would continue to provide the primary source of georeferenced navigation to the submerged vehicle fleet as well as providing links back to on-shore operators. Where this mode of operation would differ from Stage 2 development, however, is that the endurance of both ASV and AUVs alike would allow this vehicle combination to stay at sea for extended periods and,

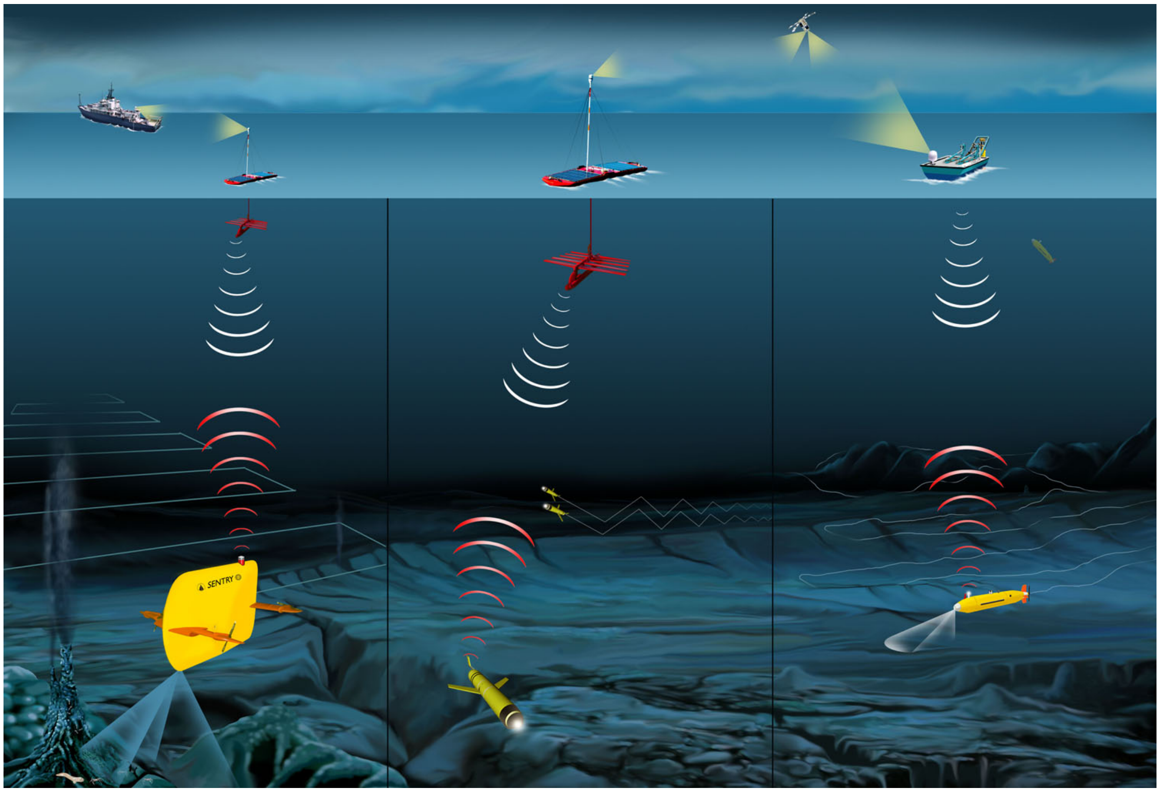


Fig. 4. Our three phase concept of operations for increasingly sophisticated ship-free deep ocean operations in the future: Left: ASV tending of conventional deep ocean AUVs (e.g. Sentry) would act as a force-multiplier in operations of a kind that are already standard, allowing the support ship to conduct over the horizon operations while the AUV is submerged without sacrificing an ability to track, monitor and even retask that AUV at depth; Center: ASV coordination of a fleet of deep ocean vehicles (e.g. gliders) over longer surveys such as hydrothermal exploration along multiple consecutive segments of ridge-crest; Right: Next generation ASVs that could autonomously launch, recharge and recover AUVs, in addition to acting as a source of georeferenced navigation to a submerged vehicle fleet and facilitating 2-way communications between those assets and a shore-based operational team would allow more thorough basin scale investigations to be conducted than have ever, to-date, been achieved without the need for global class research vessels to be dedicated to such timely deep ocean exploration.

hence, conduct surveys over the scale of entire ocean basins. While such operations would require much more sophisticated ASVs than the current state of the art, we believe that the investment would be worthwhile because the operational costs would nevertheless remain significantly more affordable, for the future of deep ocean exploration, than the costs that would be incurred if the international community were to dedicate Global Class research vessels to provide that same support.

## III. System Overview

In this section we describe progress toward a prototype system capable of autonomous tending, the first phase of our decadal vision for ship-free ocean exploration. Our prototype system consists of a Liquid Robotics Wave Glider (WG) [9] and an OceanServer Iver2 AUV [10]—each equipped with a WHOI MicroModem [11] for acoustic telemetry between the robots—and will demonstrate several enabling capabilities: (1) GPS-forwarding from the WG to the AUV for navigation; (2) remote data access and control of the AUV; (3) autonomous coordination of the WG and AUV.

For this first phase the AUV will execute its mission independent of the state of the ASV (with the exception of mission plan changes from operators relayed through the ASV). The ASV has the primary task of maintaining acoustic contact with the AUV, and the secondary task of providing navigational aiding. These are competing objectives. The ideal acoustic path in deep water is vertical, with the ASV positioned directly above the AUV. This arrangement, however, does not provide the relative horizontal motion helpful in constraining the position of the AUV. Furthermore the Wave Glider is incapable of the speeds typical of survey AUVs. A near-term objective is to explore mission-aware trajectories for the ASV that respect this constraint, ensure good communications, and ideally also aid navigation.

The acoustic exchanges between the ASV and AUV are illustrated in Fig. 5. The ASV initiates the cycle by pinging the AUV which responds with its own ping. The WHOI MicroModem aboard the ASV then reports the one-way-travel-time (OWTT) between the two vehicles, accounting for processing and turn-around time. The ASV then telemeters its latest GPS fix along with the OWTT in an acoustic message back down to the AUV. The AUV transforms the OWTT and GPS fix into a range to known point and incorporates this measurement into its navigation solution. Finally, the AUV telemeters up its state estimate to the ASV. A program running

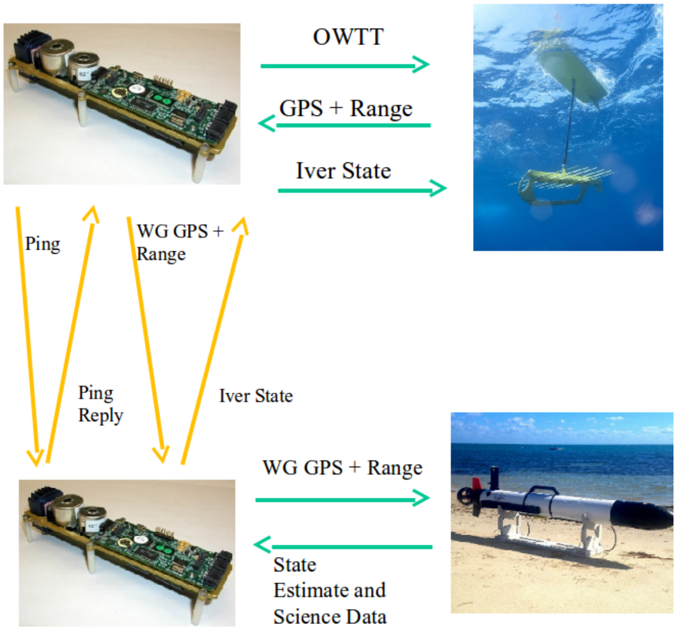


Fig. 5. Acoustic exchange overview (see text).

Fig. 6. Iver2 AUV and Wave Glider command and control module and acoustic communications payload module being readied for deployment in a local lake.

aboard the ASV then uses this position estimate along with knowledge of the AUV's mission plan to move accordingly.

### *A. AUV Navigation*

The Iver2 AUV's internal sensing suite comprised a Teledyne RDI 600 kHz Explorer Doppler Velocity Log (DVL), an OceanServer 3-axis magnetic compass and a Measurement Specialties depth sensor. We use an Extended Kalman Filter (EKF) that fused the on-board sensor data with acoustic ranges and ephemeris data from the Wave Glider, with the effect that as each acoustic range was received by the AUV, the AUV state estimate was pulled or pushed along the line connecting the current AUV state estimate with the GPS position of the Wave Glider by a distance proportional to the Kalman gain.

### *B. Initial Small Boat Tests*

An initial set of tests have been done using an *Iver2* AUV and a small boat, which served as an analogue for the Wave Glider, in a local pond. The small boat was equipped with a Garmin GPS receiver with WAAS capability, a WHOI acoustic modem topside kit, and a laptop that interfaced with the GPS and the acoustic modem and ran the coordinator program. The goal of these tests was to test the communications cycle described above, validate and tune the EKF used for AUV navigation, and assess the EKF performance when the surface craft followed the trajectory defined by the coordinator program.

Fig. 7 shows the position plots for the AUV and surface craft during these experiments. Three position estimates are plotted for the AUV — the EKF solution (red), the DVL dead-reckoning solution (blue), and, when on the surface, the GPS solution. The position of the surface vessel, as measured by the Garmin GPS, is also plotted at each instance where the EKF received a range update and used the range to externally aid the position estimate. The dead-reckoned solution was used for real-time control of the vehicle. The absence of a north-seeking fiber optic gyro precluded the dead-reckoning solution from achieving the precision reported in [12], [13].

On the first mission, plotted in the left panel of Fig. 7, we deployed the AUV to the northeast of the programmed mission and then followed it as it progressed through the mission. On the second mission, shown in the right hand panel, we followed the coordinator's recommended position. We deployed the vehicle at the START position and then, per the coordinator's recommendation, proceeded to slowly move to the center of the mission area and slowly proceed south as the mission progressed before heading north to recover the AUV at its defined END point.

The algorithm used to guide the ASV seeks to minimize an inter-vehicle squared distance metric, without regard to the quality of ephemeris data provided to the AUV. For typical grid patterns flown by mapping AUVs we anticipate that the motion of the relatively fast AUV will provide the change in relative position necessary to aid navigation. The specific distance metric used is the integral of the squared inter-vehicle

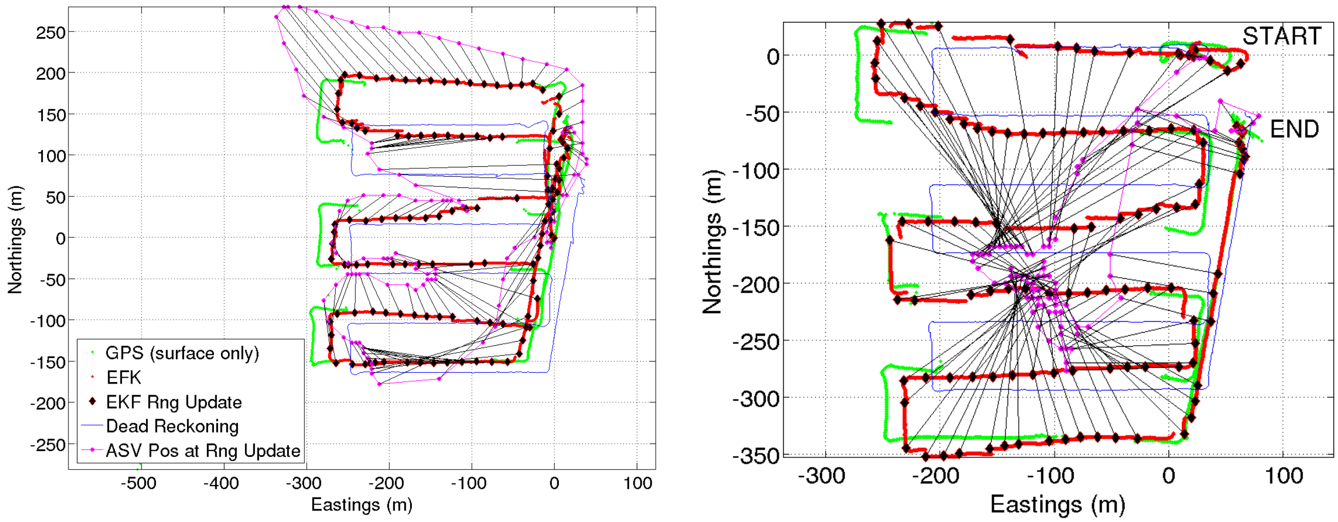


Fig. 7. Position plots for the initial missions using Garmin GPS and acoustic modem deckbox. Plots include the AUV GPS position when the AUV is on the surface, the EKF solution (at every instance and when an acoustic range update is received, the dead-reckoning (DVL + compass) solution, and the GPS position of the surface craft at each range update. During the dive plotted on the left, we followed the AUV with the surface vessel. On the second dive, plotted on the right, we drove the small boat to the position indicated by the coordinator program.

distance over the portion of the mission plan remaining at a given time (The ASV is provided with the AUVs mission plan prior to launch). In the trial shown in Fig. 7, early in the mission the ASV seeks the center of the mission plan and then moves slowly to the south as the AUV progresses along its plan.

Examination of the AUV position estimates demonstrates the EKF is correcting for errors in the vehicle navigation. The *Iver2* was using the dead-reckoning position estimate in real-time, however because of large variations in sound speed in the lake (40 m/s between the surface and the bottom) this solution was incurring significant navigation errors. These errors can be observed by comparing the dead-reckoned track with the GPS track. For example, in the left plot the dead-reckoned solution for the southern-most trackline extends further south than the GPS measurements at the beginning and end of the trackline. The EKF, which is using single ranges to externally aid the process model and DVL measurements, compares favorably with the GPS positions for the same trackline. On the second mission, where the surface vessel moved toward the center of the mission area and remained within in approximately within this 100 m by 100 m area for most of the mission, we observe numerous corrections resulting from range updates. For example, on the southern most trackline, we observe the EKF estimate gradually moves from south (at the western end of the trackline) and, as the AUV moves east, corrects its position estimate to the north. When the AUV surfaces and reacquires GPS the difference between the EKF estimate and the GPS measurements are within 10 m. In both missions, we can see that EKF is correcting for errors in navigation and providing a more accurate solution than the dead-reckoned solution alone.

Phase I of the long term vision articulated above could employ an ASV-AUV strategy similar to those used in these tests and our preliminary work suggests that this technique could allow us to use a Wave Glider deployed over an AUV survey area to accurately aid the AUV's internal navigation solution. Additional research is necessary for determining the constraints imposed by the vehicle trajectories [14].

### C. Hardware in the Loop Tests

Next we performed a series of trials utilizing Wave Glider hardware in-the-loop as described in Sec. III. One set of results is shown in Fig. 8. In this case we anchored the ASV in the center of the AUV's survey pattern for the first part of the dive and then followed the AUV for the second half.

The same data was used to generate both plots and the processing method identical to the Fig. 7 with the exception that, in the right-hand plot, we treated the GPS and OWTT information from the Wave Glider as if it were delayed by 50 s. With this compensation applied the EKF track more closely resembles the AUV's own GPS track; however, we do not yet have an explanation for the source of the apparent latency. Trials in which the vehicle navigates using the EKF solution await a solution to this problem.

## IV. Conclusion

In this paper we presented a vision for ship-free coordinated AUV-ASV operations comprising three stages: (1) autonomous tending, (2) ridge-segment scale autonomous exploration, and (3) oceanic basin-scale autonomous exploration and monitoring. The technologies necessary, reliable long range AUVs and ASVs, acoustic telemetry, and autonomy are evolving rapidly and we believe present opportunities for dramatically reducing the cost of some types of oceanographic science.

We also reported our own progress toward the first stage of this vision. While our results to date have been modest,

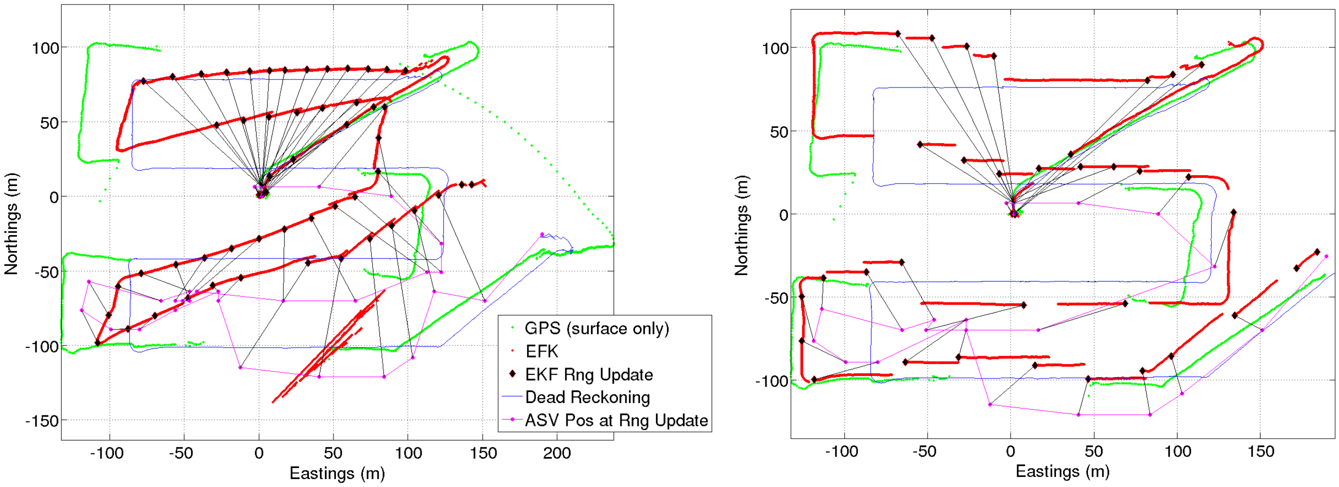


Fig. 8. Estimated position of the AUV during trials with the Wave Glider hardware in-the-loop. The left-hand plot shows poor results, with evidence of numerical instability in the filter. The right-hand plot was generated from the same data by treating the GPS and OWTT data from the Wave Glider as delayed by 50 s. In this case the EKF is able to compensate the dead-reckoned solution such that it aligns more closely with the GPS aboard the AUV.

they do serve to demonstrate the fundamental feasibility of the concept.


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