Toward an Autonomous Communications Relay for Deep-Water Scientific AUV Operations

Michael V. Jakuba, Carl L. Kaiser, Christopher R. German, Adam S. Soule
and Sean R. Kelley
Woods Hole Oceanographic Institution, Woods Hole, MA USA

***Abstract*—We are developing an over-the horizon deep-water autonomous underwater vehicle (AUV) supervision capability by introducing a second autonomous vehicle, an autonomous surface vessel (ASV) with continuous access to Iridium satellite communications, that acts as a communications gateway between operators on the ship or on shore and the AUV. This enables operators to monitor dive progress remotely, including uplinking science data and optionally modifying the AUV's mission in response, frees the ship to conduct other operations remote from the AUV, and enables new operations paradigms. An important question is whether these benefits outweigh the costs associated with managing another vehicle and the degradation in navigation and map quality that results from operating outside the range of the ship's Ultra-Short BaseLine (USBL) positioning system. We undertook trials in 2018 with the Sentry AUV and an LRI Wave Glider ASV, operating the system for a total of 15 Sentry dives. The Wave Glider was recovered once for a planned 24 hr hardware upgrade but otherwise remained deployed for nearly all of our time on station.**

We report the coordination algorithm employed, along with assessments of system performance in terms of acoustic link reliability, the impact on post-processed AUV navigation from the absence of the ship, and logistical footprint—the impact of the system on the Sentry operations team and other ship operations.

I. INTRODUCTION

Deep water mapping Autonomous Underwater Vehicles (AUVs) are capable of generating bathymetric maps with 1 m^2 resolution on scales of a few km^2 per 10–30 hr dive. Such AUVs require a vessel to support, at minimum, launch, recovery, and inter-dive maintenance. The National Deep Submergence Facility (NDSF) AUV Sentry has performed over 500 dives in water depths up to 6000 m in service of oceanographic science. Because many of the sites of particular interest are remote, e.g. mid-ocean ridges, the vessels used to access them are large, capable, and carry a science party usually numbering above 20. This translates into a wide variety of scientific activities that the ship can execute other than Sentry operations. However, the most commonly used Sentry operations paradigm calls for tending the vehicle with the ship during surveys. There is considerable value in doing so—this allows operators to monitor the dive acoustically, preview certain science data, redirect Sentry in response, and navigate Sentry in a geodetic coordinate frame using either the ship's Ultra-Short BaseLine (USBL) or Sentry's fly-away USBL acoustic positioning system. USBL improves Sentry's navigation over pure dead-reckoning and ultimately underpins creation of self-consistent georeferenced maps.

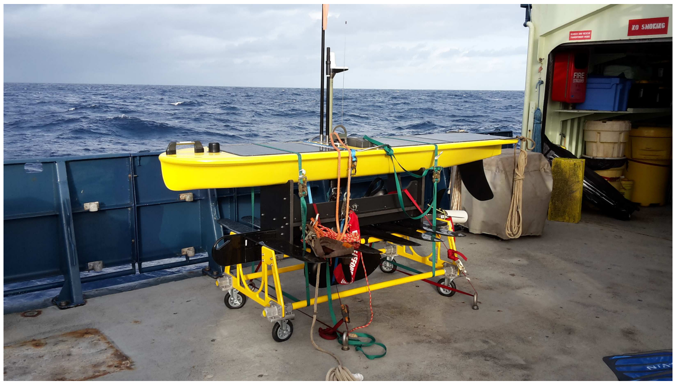

Fig. 1. LRI Wave Glider SV3 configured as a communications relay. The bulb on the "sub" houses a WHOI Micro Modem. One of the payload modules in the "float" contains a WHOI-designed Iridium modem/GPS receiver module that relays messages to and from the Micro Modem over Iridium as Short Burst Data (SDB). The relay functionality is decoupled from normal operation of the vehicle except for drawing power.

Other science activities could proceed in parallel if Sentry could operate independently from the ship, an obvious benefit. We aim to realize this benefit by adding an Autonomous Surface Vessel (ASV) to the system to act as a communications relay and thereby to retain the ability to monitor and redirect Sentry even while remote from the vehicle. However, there are costs associated both with remotely operating Sentry (navigation quality), and with fielding an additional vehicle (logistical impact, especially any additional required personnel). Our trials aimed to assess these tradeoffs, and to identify system characteristics that influence them, necessarily within the context of our particular cruise.

II. BACKGROUND

The idea of tending one or more subsea AUVs or other underwater assets by maintaining an acoustic link is not new and goes back to at least the 1980s.[1] Since then many authors have explored various aspects of the problem, including especially coupled range-only navigational aiding, e.g. [1], [2], and using an ASV as a communications gateway [3], [4], [5]. We too have previously examined coordinated AUV/ASV operations, including shallow water trials using a Wave Glider to tend an Iver AUV and provide both navigational aiding and

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[1] The Albart project https://www.nsf.gov/awardsearch/showAward?AWD_ID=8319813 was an attempt to convert a yacht for tending the Alvin submersible.

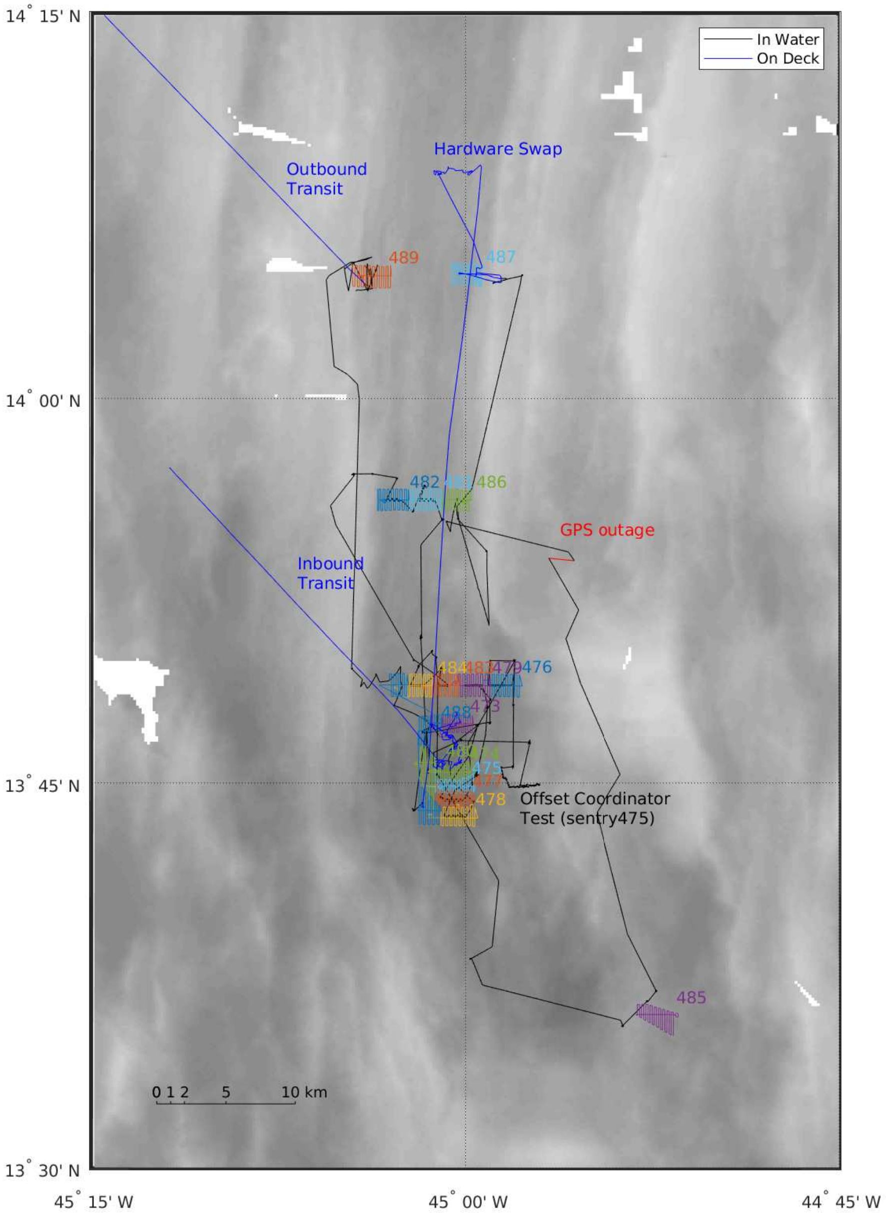

Fig. 2. Wave Glider trajectory over the course of the time on station. The GPS outage consisted of a roughly one hour period during which location data from the Wave Glider varied by large fractions of a degree and that we ultimately resolved by commanding a re-initialization of the GPS device driver via WGMS.

a communications relay [6], an experience which informs the present work.

The technical feasibility of our objectives, therefore, was not in question; however, *operational* feasibility within the specific context of deep-water scientific AUV work is a more demanding metric. To demonstrate operational viability, adding an ASV must result in a net positive return on scientific yield in both the short (one cruise) and long term (several years). For example, the costs of adding an ASV might require extra personnel on board (directly subtracting from bunks available to the science party), recurring costs in the form of satellite airtime and maintenance, increased operational burden on personnel normally focused strictly on AUV operations, logistical considerations including especially shipping, and the capital cost of the ASV itself plus any payload. This work examines short term viability over a single cruise.

The Wave Glider [7] is a particularly attractive ASV to tend a deep-water AUV like Sentry that performs primarily surveys covering a few km^2 per dive. Wave Gliders are field-proven and commercially available, acoustic payloads have already been integrated into Wave Gliders by WHOI's acoustic communications group for other projects [3], [4], and most importantly, Wave Gliders have effectively unlimited endurance. Our experience in 2012 [6] demonstrated the value of this latter property—unlike a vehicle requiring launch and recovery on the same schedule as the AUV that would substantial burden to operations teams and clutter the deck, an ASV capable of remaining deployed between dives, ideally for an entire cruise, places relatively little burden on teams, assuming it also requires little or no oversight between dives (e.g., holds station or transits autonomously). Our present work is similar to [5], in which the authors used a Wave Glider to autonomously track a Tethys AUV to provide a WiFi "hotspot" for rapid download of data from the AUV's brief surfacings, and a communications relay of the same data to shore. Like us, they ran software external to the Wave Glider itself to aggregate the necessary data from the AUV and ancillary data into a mission plan delivered to the Wave Glider via satellite. Our application is distinct in that we relay acoustic rather than radio frequency data, operate from a ship rather than shore, and operate in concert with a ship-deployed AUV launched and recovered daily, as opposed to the shore-deployed Tethys AUVs that operate for weeks at a time [8]. I.e., the factors governing operational viability differ.

III. SYSTEM OVERVIEW

We used an LRI Wave Glider SV3 as the mobile gateway to relay acoustic communications over Iridium when the ship was out of direct acoustic range. Our Wave Glider was equipped with a custom payload module consisting of an integrated GPS receiver and Iridium transceiver that communicate with a WHOI Micro Modem 2 [9] mounted on the Wave Glider's "sub," the winged propulsion device suspended below the surface expression. The Wave Glider supplies power to these payloads but otherwise they operate independently. Two software modules, both running ship-side, provide the interface between Sentry operations and the Wave Glider:

1) relay: wraps the Iridium interface to the Wave Glider payload so that it appears like a second topside acoustic modem (redundant with the modem physically located on the ship).
2) coordinator: commands the Wave Glider to waypoints determined by Sentry's mission plan and its progress along the plan, and provides Wave Glider status for display ship-side.

The coordinator wraps LRI's web-based Wave Glider Management System (WGMS) interface and therefore requires Internet access (though bandwidth requirements are minimal). We previously ran an equivalent of the coordinator directly on a Wave Glider SV2 [6], [10]; and while there are advantages to that approach, running the coordination software on the ship eased integration with other ship-side processes, and enabled a more rapid development cycle.

IV. WAVE GLIDER OPERATIONS

In May/June 2018 we deployed our Wave Glider from R/V Atlantis along with AUV Sentry and the Alvin submersible on a 32 day cruise to the Mid-Atlantic Ridge (MAR) at 13° N. Soon after arrival on site, we deployed the Wave Glider, then gradually integrated it into Sentry operations over the course of several dives to allow for debugging and tuning the relay and coordination software.

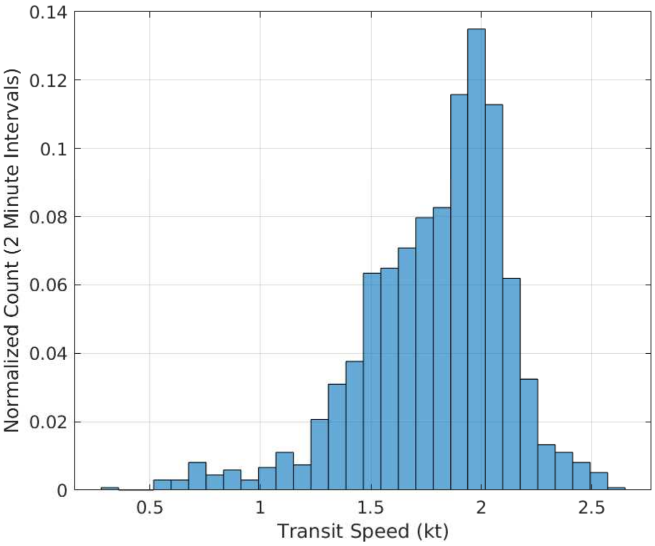

Fig. 3. Straight-line Wave Glider transit speeds observed during the cruise. Surface currents likely account for most of the variability. Combined seas were consistently 2–3 m throughout the cruise.

We added visualizations of the Wave Glider's position and current target waypoint to the Sentry watch-standers' navigational plotter, *navG* [11]. We also added controls to manually command a waypoint (which also disabled automatic waypoint generation), to re/enable automatic waypoint generation, and to switch on/off the relay hardware, the latter to limit Iridium airtime costs. These controls proved sufficient to manage Wave Glider operations and for the most part avoided frustrating (though functional) web-browser interactions with WGMS over the severely constricted shipboard Internet (the navigation interface, which relies on google maps, proved essentially unusable). We did use the WGMS web-browser client for the few additional commands necessary to execute launch and recovery, occasionally to check on battery level and other subsystems, and once to re-initialize the Wave Glider's GPS after an apparent failure.

A mirrored *navG* display on the bridge provided the ship's crew with a graphical indication of all assets, including the Wave Glider. Since nearly all Sentry operations occurred at night, the Wave Glider's mast light, visible for at least 5 km in 5–9 ft seas, proved to be a comforting visual indicator of its position. During the day we typically commanded the Wave Glider well off site or staged it at the next dive site if distant. The Wave Glider's batteries remained above 85% charge throughout the cruise despite continuous use of the mast light.

In total we used the Wave Glider to tend Sentry on 15 of 17 dives (Fig. 2). It was recovered once during that period for a planned 24 hr hardware upgrade to enable high-precision acoustic ranging (Sec. VII). The scientific objectives for the cruise called for mapping and other activities at four sites,

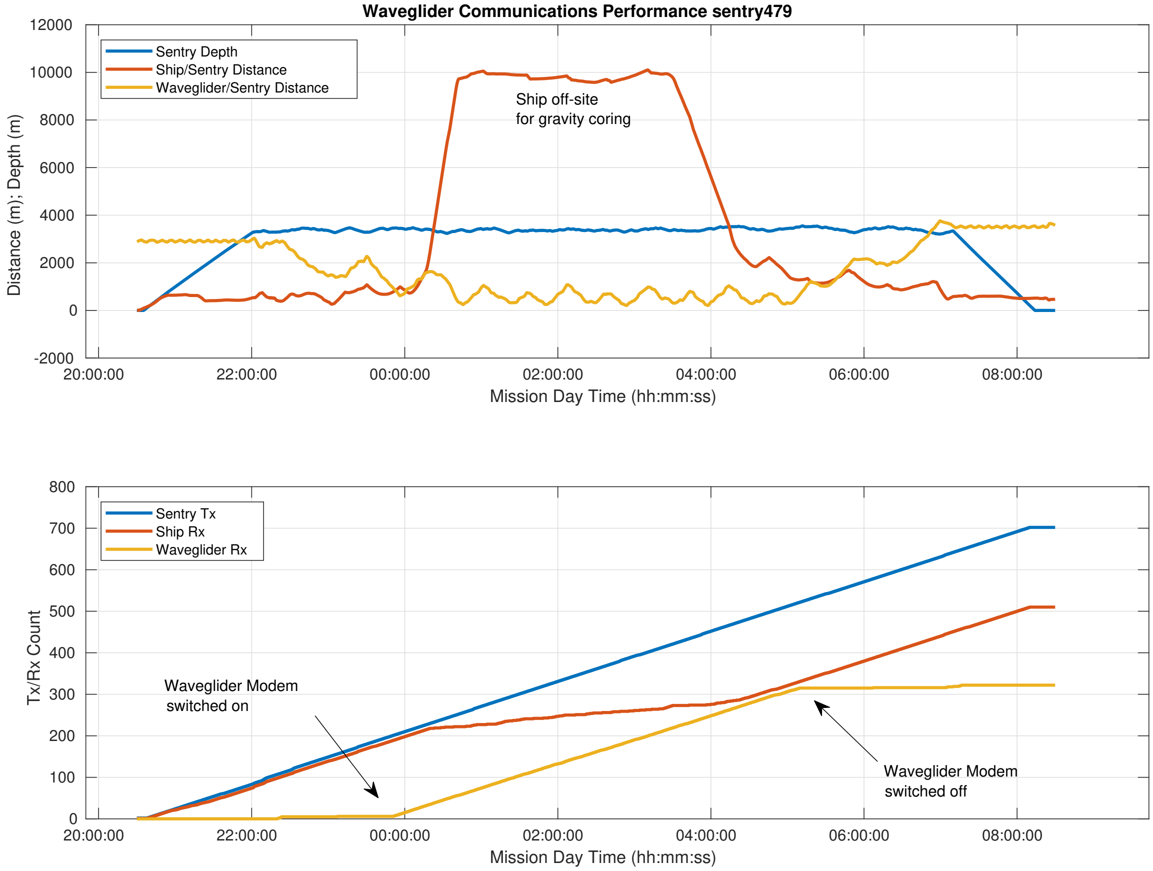

Fig. 4. Relay communications performance during sentry479 illustrating the hand-off of tending duties between the ship and Wave Glider. After deploying Sentry and tracking it with USBL to the seafloor, the ship left the site for several hours to perform a gravity core. At 10 km distant the ship's Micro Modem still received some packets, although at about half the rate received by the Wave Glider. The ship returned for Sentry's ascent and the Wave Glider moved off site. The Wave Glider's modem was switched off when redundant with the ship's to save on Iridium airtime costs.

spaced N–S at approximately 10 nmi intervals along the ridge axis. The Wave Glider's modal straight-line speed of 2 kt (Fig. 3) was sufficient to transit between sites during the day, between overnight Sentry dives.

A typical Sentry dive lasted 10–12 hours, with the descent and ascent consuming 3 hrs combined. The ship remained on site after descent for 1–2 hours and returned again about 1 hr prior to ascent. The intervening 4–7 hours were therefore available for other off-site activities. Nine gravity cores, an operation lasting 2–3 hours plus transit, were attempted (8 successfully) during these windows.

Dive sentry488, the second to last of the cruise, was atypical in that it spanned nearly 36 hours. Including charging and maintenance time this yields a 48 hr dive cycle in place of the usual 24 hr cycle. Leaving Sentry untended for the duration would yield 20+ hours for off-site activities, a benefit that was realized on the dive, but the implications of a 48 hr cycle in terms of scientific yield are more significant: an extra 12 hours survey time per 48 hours. Sentry's battery capacity is such that it cannot survey at full speed for 36 hours, but it can still cover more ground at slow speed in 36 hours than in 24 hours at full speed.

Dive sentry488 generated a map of 37.5% greater coverage than two normal 24 hr overnight dive cycles combined (10.87 km^2 vs. 3.95 km^2 average coverage from the previous 15 dives). The Wave Glider allowed us to monitor Sentry throughout the dive, allowed the ship to perform its normal planned daytime activities at a site 20 km distant and to conduct a gravity core the second night. Our approach to this dive was conservative–the ship did not leave Sentry the first night, and it returned breifly after daytime operations to geo-reference the vehicle, nevertheless, the ship spent a total of 16 hours off-site, performed normal daytime activities unimpeded and acquired a "bonus" sample (the core), all while Sentry delivered more coverage in the same period.

V. AUV/ASV Coordination

Our primary objective called for automatic control of Wave Glider position to maintain good acoustic communications with Sentry, ideally a near vertical path. In fact, acoustic connectivity was so good once Sentry neared the bottom (Fig. 4) that the Wave Glider could have simply held position

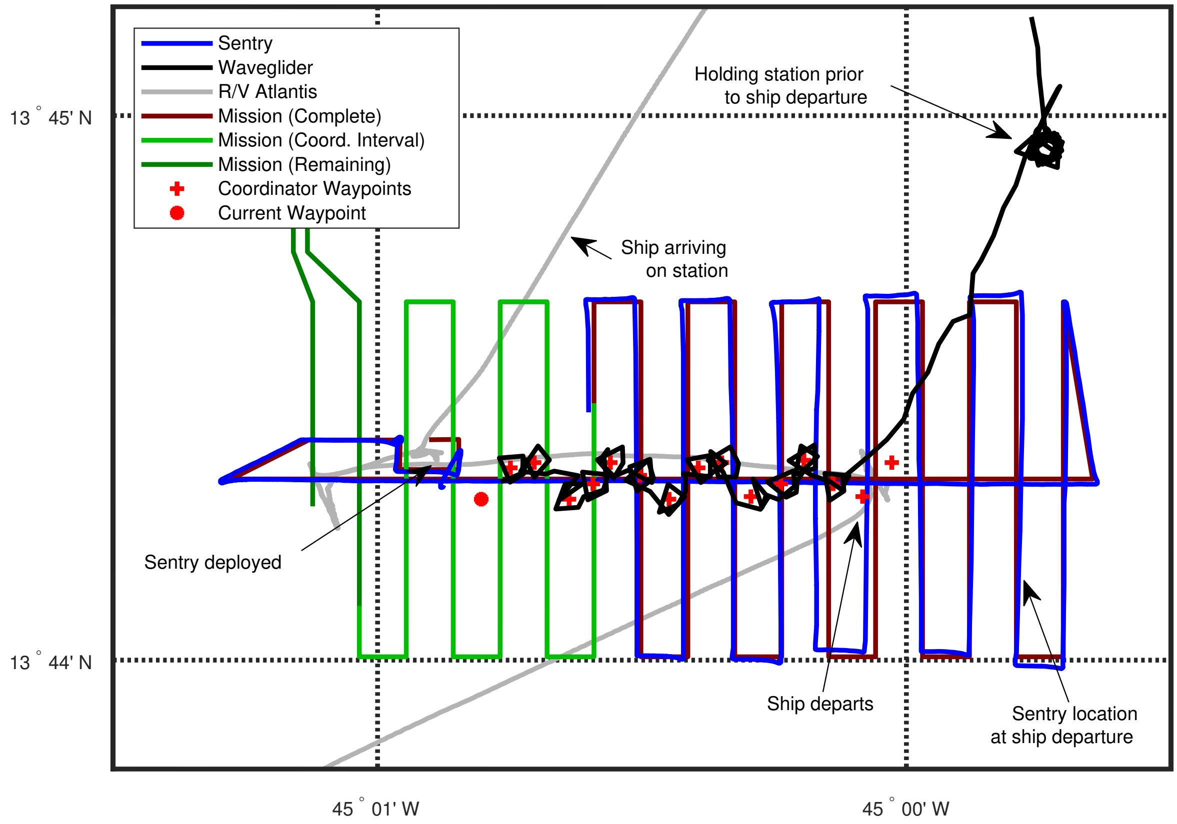

Fig. 5. Wave Glider, Sentry and ship trajectory during dive sentry477 illustrating automatic waypoint generation for the Wave Glider. The current waypoint (red) was computed as the spatial centroid of the portion of the mission plan highlighted in light green. The Wave Glider's speed was such that it spent most of the survey orbiting commanded waypoints. Updated waypoints were uplinked to WGMS every 10 minutes during dives.

at any convenient location within or near the 2–3 km^2 footprint of most surveys on the cruise. However, not all surveys consist of only one "block" and, absent a tending ship, there is no compelling need *not* to use the best possible acoustic channel.

We designed the coordination algorithm to keep the Wave Glider near Sentry, slightly ahead with respect to Sentry's mission plan, and to require relatively less motion to accommodate the Wave Glider's weather-dependent and sometimes slower speed. The coordination algorithm is straightforward: given Sentry's mission plan and its currently executing trackline segment (reported acoustically), create a window consisting of a certain number of trackline segments ahead of the current segment, compute the spatial centroid of the windowed segments, and finally command that location as a target waypoint to the Wave Glider.

Fig. 5 illustrates the behavior of the algorithm and our use of it in practice. Without external aiding, Sentry's position estimate on its descent can drift significantly (100s m). Standard operating procedure calls for using the ship's USBL to track Sentry to the seafloor and correct its position estimate, after which Sentry dead-reckons using on-board instrumentation. The survey depicted, like most, included a "crossing line" running perpendicular to the usual "lawnmower" grid pattern. The ship departed only after providing USBL aiding for duration of the crossing line. The crossing line provides a means of tying bathymetry data from the tracklines of the grid pattern into a self-consistent and geo-referenced map using tools built into the multibeam processing suite mbsystem [12]. After departure of the ship we enabled the coordination algorithm, which generated the series of weakly undulating waypoints in the figure. Prior to ascent we called off the Wave Glider, and the ship returned to geo-reference the vehicle's position once more.

VI. IMPACT ON NAVIGATION AND MAPPING

Most Sentry dives are devoted to bathymetric mapping of the seafloor. The current multibeam sonar system works well at a height-above-bottom of 70 m. At this height Sentry's 300 kHz RDI Workhorse Navigator Doppler velocity Log (DVL) is well within bottom-lock range. Attitude from a iXBlue Phins combined with bottom-tracking velocities from the DVL yield real time unaided navigation sufficient to execute multibeam surveys covering a few km^2 without gaps. External aiding is necessary, however, to initialize Sentry's position on the seafloor after descent. Since 2010 we have used either the ship's USBL or a dedicated fly-away system for this purpose. Thereafter external USBL aiding serves to constrain dead-reckoning drift during post-processing via a complementary filter.

Compromised maps would represent an unacceptable trade for a few hours of extra ship time. Prior to deploying the Wave Glider we undertook a data-denial experiment to examine the impact of reduced navigational aiding on Sentry's mapping products. Fig. 6 illustrates the nominal product from dive sentry474 with USBL aiding throughout. Fig. 7 illustrates the result of removing USBL aiding from the majority of the dive. The impact is qualitatively imperceptible at the resolution plotted.

In fact the difference between post-processed navigation with and without USBL aiding is significant on the scale of features in the maps. The USBL-denied and baseline solutions differed by as much as 20 m during the middle portion of the dive for the dive shown. Upon loss of USBL aiding the USBL-denied solution begins to track the real-time dead-reckoned estimate until restoration of USBL aiding near the end of the dive. However, that discrepancy is largely obscured in the maps by the fact that the error growth is relatively small between adjacent parallel tracklines with overlapping swaths.

The crossing line, with benefit of USBL aiding, provides a means to remove gross distortion by registering bathymetry from individual tracklines back into a consistent geo-referenced coordinate frame. We leverage standard tools from mbsystem for this purpose. As these tools require subjective human judgment, the maps in Figs. 6 and 7 do not have these additional corrections applied.

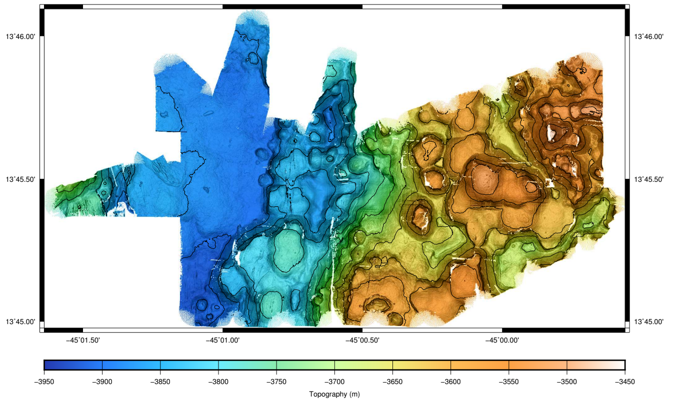

Fig. 6. Multibeam bathymetry from sentry474, baseline processing using USBL fused with dead-reckoned navigation.

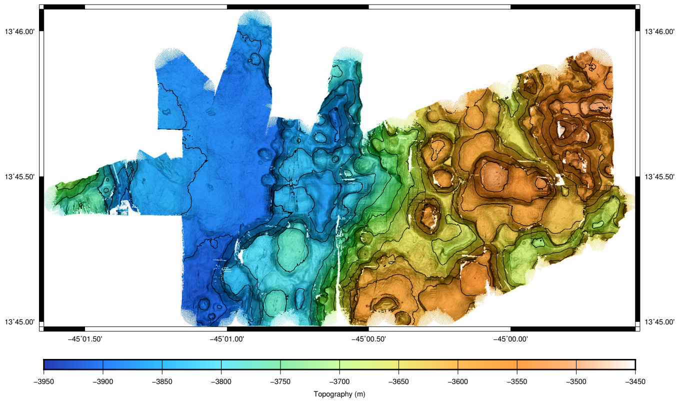

Fig. 7. Multibeam bathymetry from sentry474, baseline processing identical to that in Fig. 6 only with USBL artificially withheld to simulate the effect on map quality of leaving Sentry untended for the majority of its dive. The maps are qualitatively indistinguishable.

VII. NAVIGATIONAL AIDING

ASVs with considerably more energy and power can carry USBL systems of similar quality to the ship-board system used with Sentry [13]. These ASVs impose a larger logistical footprint than the Wave Glider used here, but ASV platforms and payloads are experiencing rapid development. Absent an extant sufficiently low power USBL the Wave Glider can still provide navigational aiding by acoustically ranging to Sentry. Fig. 8 illustrates the idea. Successive ranges between the Wave Glider and Sentry are propagated forward according to Sentry's telemetered dead-reckoning to yield a running fix. We disabled automatic waypoint generation for the dive depicted, sentry489, instead guiding the Wave Glider manually to positions likely to produce range rings that intersect at steep angles and thus provide good position constraints. The ship remained on station throughout the dive to provide USBL positioning for comparison with the running fix results.

The running fix plotted was some 3 times noisier than the USBL, and the errors also display considerable structure. The structure is unsurprising as the error properties of a horizontal range are strongly dependent on the ratio of the depth to the slant range (ratios approaching 1 yielding the weakest constraints in horizontal range), and the error properties of a running fix are, in turn, a conglomeration of the geometries of the member ranges. A running fix provides a simple and nearly stateless (i.e. robust) means of corroborating georeferenced vehicle location in real time because it relies only on relative motion estimated by dead-reckoning between ranges. Compromised dead-reckoning would compromise the fix, but in this case range rings from successive measurement would also fail to agree on a vehicle location, providing operators with an indication of a likely dive-ending problem.

In post-processing the running fix approach is too crude and would be replaced with a suitable non-linear estimator (e.g. the Extended Kalman Filter used by us for this purpose [6] and evaluated in [14] against other nonlinear estimators). More importantly, to make range-based navigational aiding a viable stand-in for USBL aiding in post-processing will likely require a faster ping rate (USBL fixes arrive several times a minute, whereas the Wave Glider transmitted ranging pings only once every five minutes during sentry489), and better use of the Wave Glider's mobility to optimize ranging geometry. The latter is doable [2], [15] because Sentry's future trajectory

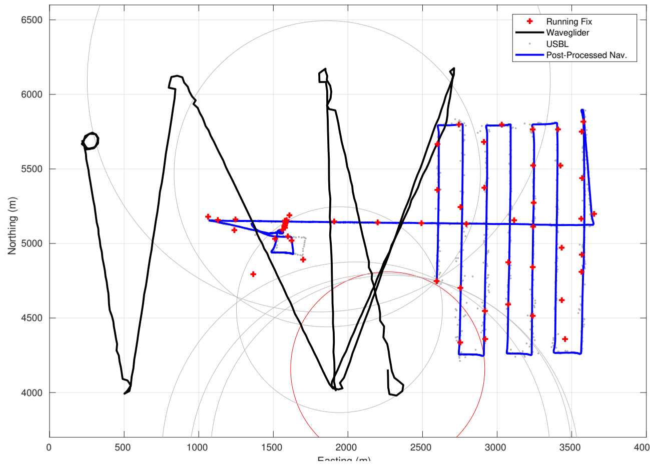

Fig. 8. Wave Glider and Sentry trajectory during dive sentry489 showing estimates of Sentry position (red crosses) from ranging pings initiated at the Wave Glider and processed using a 7-range running fix. We drove the Wave Glider manually for this dive. The ship remained nearby to provide ground-truth navigation in the form of high-rate USBL.

is known and deviations from the mission plan typically small.

VIII. CONCLUSIONS

The Wave Glider had minimal logistical impact on Sentry operations or other operations with the ship. Several factors account for this. Most importantly the Wave Glider stayed deployed for nearly the entire time spent at the study area (except one 24 hr period). It reliably achieved speeds of >1 kt, allowing us to move it at will between three study sites, each separated by about 10 nmi, during daily Alvin dives while Sentry recharged. A minimal set of controls, integrated into Sentry's normal topside monitoring system, proved sufficient to manage the Wave Glider: command a manual waypoint, engage/disengage coordination, and turn the Micro Modem payload on or off.

Although our cruise included a bunk dedicated to operating the Wave Glider, our experience suggests that future cruises will not. The benefit to science was real—an additional 4–6 hours of ship time per 12 hour Sentry dive, with negligible impact on map quality. On the other hand, shipping the Wave Glider would increase the current two container (20' ISO) footprint of the Sentry system significantly. Any future use of a Wave Glider or other ASV for tending Sentry will have to consider these competing costs and benefits.

ACKNOWLEDGMENTS

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