Fully characterizing the Earth system and predicting its likely response to events such as global climate change requires increased understanding of the processes active in the ocean's interior, which, in turn, requires access to a continuity of data, at the global scale, from this deep, dark and remote environment [99]. While modern satellite oceanography provides key observations of the ocean-climate system continuously, with global-scale coverage and in real time, it primarily observes the surface microlayer of the ocean and provides limited insight into the processes occurring within the ocean interior—a region that provides the largest contiguous habitat for life on Earth as well as representing the largest known active reservoir in the global carbon cycle. Access to data in the deep ocean interior is difficult to obtain because the necessary observations can only be made from instruments and/or vehicles deployed from dedicated research ships, which typically remain at sea for periods up to their endurance limits (roughly 1 month, port-to-port). In addition, it is difficult to deploy ships to the most remote parts of the ocean, such as the central South Pacific or Southern Ocean, which represent some of the largest and, hence, most representative environments for both life and biogeochemical cycling in the deep ocean. Real-time continuous data are becoming available at a few discrete locations via the NSF's Ocean Observatories Initiative in the US and other programs overseas, but what is urgently required to meet US Ocean Research priorities over the next decade is an ability to obtain an increasing understanding of key processes active throughout the deep ocean on a persistent basis [1].

Technological developments over the past two decades have provided US scientists with an impressive array of new deep-diving and long-endurance vehicles, such as autonomous underwater gliders (AUGs)[1] [98, 111, 27], autonomous underwater vehicles (AUVs) [2, 17, 49, 23], and long-range AUVs (LRAUVs) [34, 11], equipped with the relevant sensor packages and with increasing scales of autonomy, and that could reasonably be expected to provide coverage suitably global in scale for future science needs. What continues to elude our research community, however, is the ability to navigate those assets over long distances while submerged, *and* while retaining their autonomy. Autonomy (freedom from an attending research ship in this context) represents a critical step toward realizing a cost-effective observation capability on a global scale. Improved subsea navigation for long range ocean observing platforms will enable: *(1)* accurate position estimates of measurements to be obtained in the deep ocean interior; *(2)* precisely navigated observations around seafloor topography; *(3)* new observation strategies that will increase the density and cadence of observations in the ocean's interior; and *(4)* improved water current measurements from mobile robots through better estimates of the robots' through-water velocity (AUGs current estimates presently rely on global positioning system (GPS) fixes available only at the surface, from which only depth-averaged current may be computed — the proposed navigation advances would provide submerged position estimates that enable computation of current *profiles* resolved in depth).

The rapid attenuation of radio frequency (RF) signals in water precludes using GPS in the ocean interior, and estimating horizontal position in the ocean is especially challenging and typically requires combining *internal* navigation estimates from vehicle models (e.g., on gliders) or strapdown sensors with *external* navigation measurements ([80, 62] provide surveys of the existing state of the art). Furthermore, because of disparities in size, available energy, cost, and operating domains, the navigation methodologies used by underwater robots vary enormously. For example, power-hungry fast surveying AUVs (e.g,. [65, 97, 49]), use Doppler velocity logs (DVLs) and inertial navigation systems (INSs) to internally estimate the AUV position to within 0.1% of distance traveled [18, 117, 63] and fuse these estimates with external acoustic position measurements ($\sim$10m accuracy) — e.g., ultra-short-baseline (USBL) [88, 91, 5, 79, 77], long-baseline (LBL) [53, 76], single-range two-way travel time (TWTT) navigation systems [86, 67, 104, 6, 35, 85], or short-baseline systems [118] — to provide the superior navigation required for tasks such as bathymetric mapping [20, 59, 61]. This superior navigation is not without penalty, as *(a)* the internal sensors are expensive

[1] We use the phrase 'autonomous underwater glider' or AUG for gliders such as the Slocum Webb or Seagliders.

($\mathcal{O}(10^{4-5})$USD) and power consumptive ($\mathcal{O}(10^1)$W); and *(b)* external navigation aids require a ship to either deploy LBL transponders or remain near the AUV to provide USBL fixes.

AUGs occupy the other end of the navigation spectrum. Their small size and miserly power budget precludes using many of the sensors used by larger AUVs and the sensors they do carry must be low power. At present, GPS is the only aiding method available and can only be used on the surface. While submerged, AUGs rely on internal dead reckoning estimates based on velocities from a hydrodynamic vehicle model. However, the quality of these estimates depends on the fidelity of the models and cannot account for external forces such as water currents. In fact, water currents are estimated as the discrepancy between the expected model-based surfacing location and GPS, yielding a single vector representing depth-averaged current, which is itself subject to the accuracy of the model for the AUG's hydrodynamics. Consequently, the internal navigation error of a glider is high — e.g., [22] reports errors of ∼13% of distance traveled while [90] reports ∼50% of distance traveled. The result is navigation errors on the orders of 1-10km, with error increasing the deeper an AUG dives, and currents cannot be resolved by depth. Traditional acoustic navigation methods are not feasible as they suffer from two deficiencies: *(1)* the glider must acoustically transmit (which incurs a significant energy penalty); and *(2)*, as in the AUV case, it requires costly external infrastructure. As a result, the status quo is to operate gliders without any subsea navigational aiding. While navigation errors of this magnitude are sufficient for many present glider missions, this limitation constrains many deep glider missions — improvements in AUG navigation would enhance present missions and enable new ones.

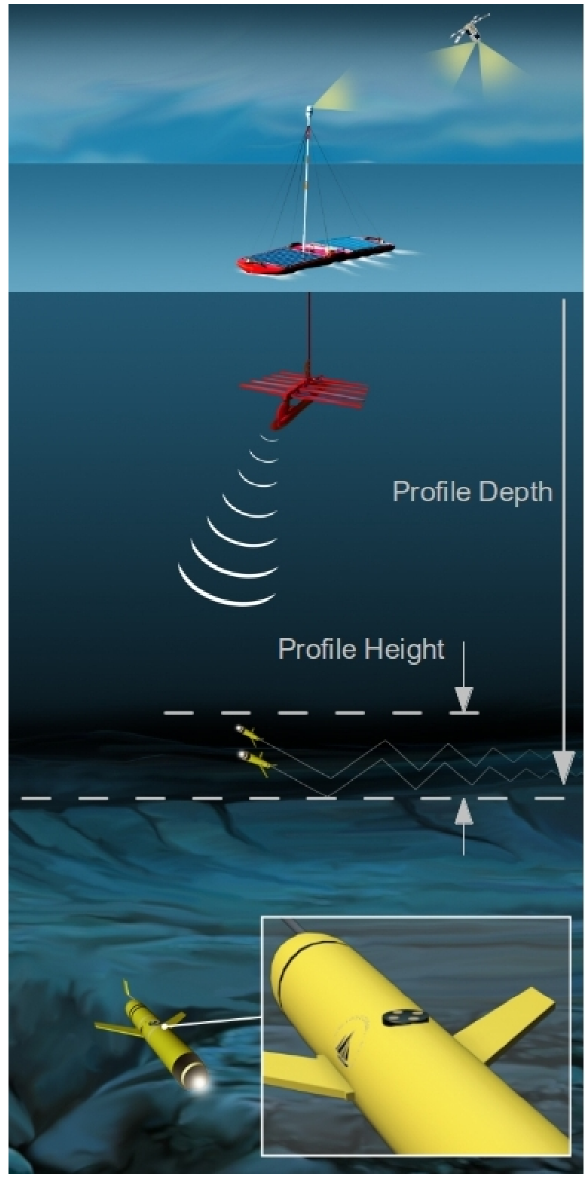

Figure 1: Conceptual image of our proposed OWTT-iUSBL system showing an ASV providing acoustic range and position information to a fleet of gliders. The inset shows the transducer installed on the glider. The transducer contains a four element array that measures the range, azimuth, and elevation from the glider to the ASV. Our definitions of *profile depth* and *profile height* are also illustrated.

We propose to develop and test a low-power acoustic positioning system that overcomes these existing obstacles and enables accurate externally aided navigation in the ocean interior. Figure 1 illustrates our proposed research concept. An AUG (or fleet of AUGs) operates at depth while an ASV follows on the sea surface. The ASV transmits its geo-reference position to the AUGs at a regular interval synchronized to GPS time. Each AUG then independently employs a precision time base and array processing to determine its position relative to the ASV. Each ASV combines this relative position estimate with the ASV's position encoded in the received packet to compute its geo-referenced position.

We call the proposed system One-Way Travel-Time Inverted Ultra Short BaseLine (OWTT-iUSBL). A feasability analysis of the acoustic and navigation performance (Section 2.2) shows that this system would improve navigation accuracy by an order of magnitude over current practice, at a power consumption compatible with the energy budgets of AUGs and other long-endurance vehicles [58]. Furthermore, the ability to provide geo-referenced navigation from an ASV enables an autonomous mobile navigation infrastructure independent of expensive ships and as discussed in a review of the Prior Art (Section 2.1) with hardware that is cheaper, less power consumptive, and more scalable to multiple vehicle operations than existing commercial solutions.

OWTT-iUSBL would also enable a new operational paradigm for AUGs — *deep-profiling*, in which the AUG dives to a profile depth and then vertically undulates within a depth band. Typical shallow-diving AUGs use subsurface undulating profiles [112], but deep diving AUGs surface after every dive [27]. Both spend a similar amount of time submerged before re-surfacing for a GPS fix. Deep-profiling can potentially increase the number of high-value observations on missions where the science dictates a limited portion of the deep water column is of interest; however, deep-profiling comes with the penalty of an increased interval between external navigation aiding from GPS. The technology developed in this proposal would overcome this limitation and, as shown in our performance analysis (Sec. 2.2), in the deep ocean deep-profiling would provide *more* measurements at depth per deployment *despite* the increased power required by more frequent pumping and the OWTT-iUSBL system *while simultaneously providing an order of magnitude improvement in navigation*. Furthermore, the synchronized transmission of a single acoustic packet from the ASV simultaneously allows any nearby asset equipped with a OWTT-iUSBL to also estimate its position. This enables novel operational paradigms in which a fleet of AUGs (or AUVs, LRAUVs, Lagraingian drifters, etc.) all have access to mobile precision positioning that enables motion coordination for spatially dense sampling at depth.

Revisions from 2015 Submission — This proposal has been updated to reflect comments by reviewers of our prior submission to the OTIC program. Specifically, this resubmission: *(1)* focuses on the specific use case of OWTT-iUSBL for navigation of AUGs (including the installation and testing on an AUG) and better defines how this concept distinguishes itself from the competitive landscape (Section 2.1); *(2)* identifies specific science questions in differing domains that would benefit from this technology over the duration of this proposal (Section 1) including insights gained in the past year that illustrate why improved autonomous navigation in the deep ocean interior is so important; and *(3)* presents an acoustic analysis that shows the potential performance of the system (Section 2.2) as well a more detailed discussion of the array design and the PIs' prior experience in this area (Section 2.3).

1 Science Drivers

Facilitating an accurately navigated persistent presence for the interior of the deep ocean has the potential to transform how oceanography is conducted. In the short term (i.e., by the end of this proposal), this technology has the potential to add new capabilities to short term process studies that either require or would benefit from accurately navigated deep-water measurements and increase the productivity of valuable ship time by enabling deeply submerged AUGs to remain at depth for days at a time. More broadly, this work is poised to revolutionize the scope of projects that can be undertaken by vehicles that have the endurance to be deployed, unsupported by research ships, for weeks or months to improve our understanding of the oceans — e.g., deep-diving AUGs and LRAUVs — and provide a foundation for teams of these vehicles and an attending ASV to undertake basin-scale surveys of the seafloor and overlying water column with improved navigation and a vastly reduced need to surface. Furthermore, the low cost and power of this navigation system makes it readily adaptable to stationary ocean assets such as buoys, instrumentation installed on the seafloor or ice-tethered profilers, thereby providing navigation infrastructure for any asset equipped with a OWTT-iUSBL system. While this proposal does not address any of these science questions per se, here we highlight two science drivers for this technology — additional examples of science applications are discussed in Section 3. However, the benefits of this project extend to any domain

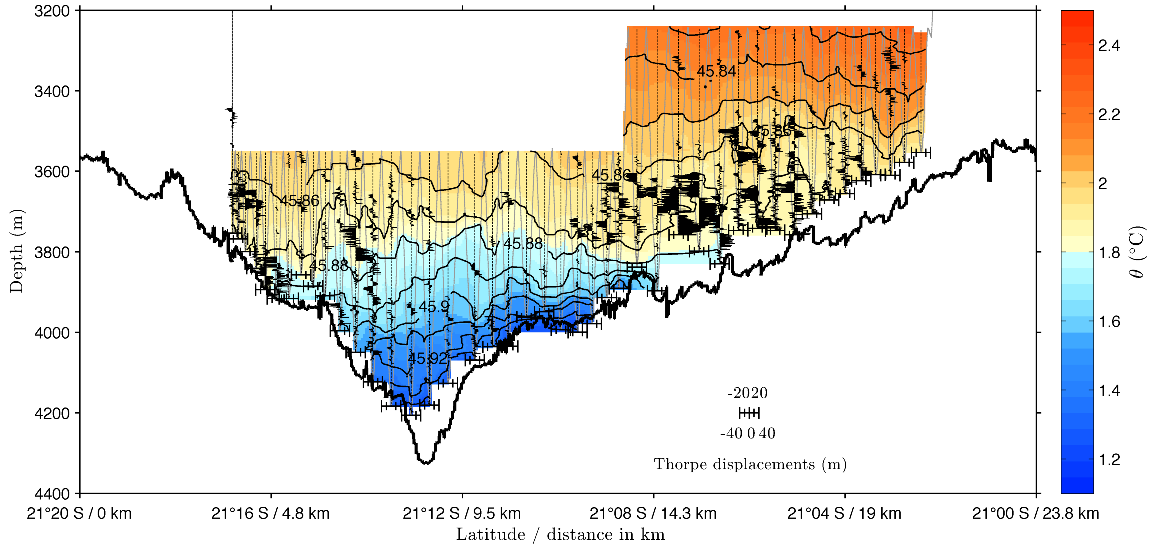

Figure 2: Hydrographic tow-yo section of potential temperature (colors), potential density (labeled contours) and Thorpe-displacements (dotted profiles with horizontal black bars) across a ridge-flank canyon on the western flank of the Mid-Atlantic Ridge near 22°S. Horizontal resolution near the seabed is ≈400m.

where accurate low-power deep-water navigation would enhance ocean observation and provides a broader impact for this work.

1.1 Physical Oceanography

While the spatial resolution of numerical circulation models keeps increasing, many of the important processes acting along the boundaries of the ocean are associated with scales that remain well below the grid scale of the models. In addition to being hard to model, the scales of many oceanic boundary processes make them difficult to resolve observationally, too. In particular, bottom-boundary-layer processes in regions with steep topography, such as mid-ocean ridges, seamounts and islands, continental slopes, shelf-slope canyons, fjords, etc., often require horizontal resolutions better than 1km. This is illustrated with a meridional CTD section across an abyssal canyon in Fig. 2 where some of the dominant patterns are associated with scales barely or not at all resolved by the 300-400m horizontal resolution of the tow-yo cast. With ship-based sampling, such tow-yo casts are only possible in good weather, and significantly higher spatial resolutions are not practical. In case of untethered microstructure measurements for turbulence and mixing the problem is even worse as only unguided full-depth profiles are possible, except when expensive AUVs (with high noise levels) are used [102]. These considerations illustrate the need for new strategies for observing bottom boundary processes that both decrease the dependency on surface vessels while simultaneously improving the accuracy of low-power mobile robots. A single AUG will allow comparable sampling to what is possible with conventional LADCP/CTD tow-yos, while additionally providing a stable platform for microstructure measurements *and* freeing the surface vessel to carry out other work. A sufficiently large fleet of AUGs will allow resolution of both short time and small space scales, something that is not possible with present technology.

While there is plenty of interesting topography within reach of the 1000m depth range of the glider in this proposal, the maximum depth range of the OWTT-iUSBL system (6000 m), will allow investigation of turbulence and mixing on the flanks of slow-spreading mid-ocean ridges. These regions are particularly important *(i)* because of their area (the flanks of slow-spreading ridges account for more than 50% of the seafloor area of both the Atlantic and Indian Oceans) [100]; and *(ii)* because they provide the bulk of the buoyancy fluxes required to close the Antarctic Bottom Water (AABW) overturning cell [93, 71, 70]. The flanks of slow-spreading mid-ocean ridges are corrugated by quasi-regular 500–1000-m-deep “ridge-flank canyons,” where cross-flank pressure gradients are balanced by up-flank (i.e. along-canyon) flows of AABW [100]. Within the

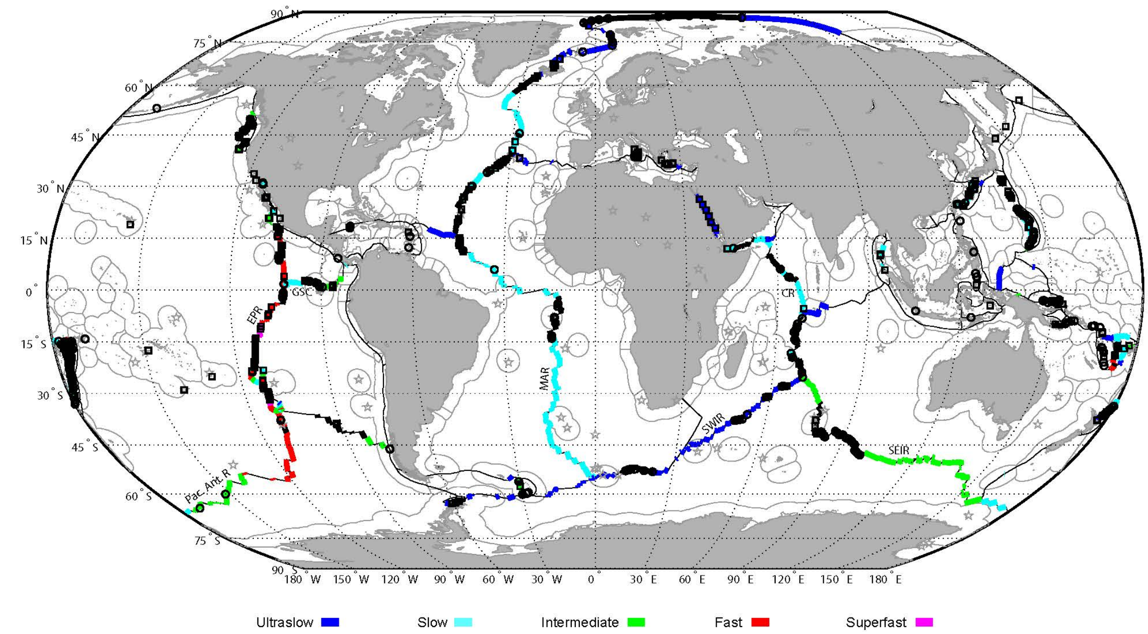

Figure 3: Distribution of different types of mid-ocean ridges (MORs). Significant portions remain unsurveyed including vast expanses in remote regions. For example, the Southeast Indian Ridge (green line in the lower right hand side of the map) is 1000s of km long. Ship based methods are expensive and of limited duration (transit times alone approach 10 days to station) and motivate autonomous techniques. [41]

ridge-flank canyons there are hot-spots of turbulence associated with steep small-scale topography [81, 101]. While barely resolvable with ship-based sampling (Fig. 2), deep AUGs equipped with the OWTT-iUSBL will be ideally suited to sample these sites.

Neutrally buoyant floats for Lagrangian experiments are another potentially important application for the OWTT-iUSBL system in the context of physical oceanography. With present technology, tracking floats requires acoustic transponder networks, which are expensive to install and maintain in the open ocean, and typically not feasible for regions of rough topography, except at small scales. In particular, Lagrangian observations near small-scale topography are currently only possible with expensive and time consuming tracer release experiments (e.g. [68, 55]); continuous trajectories are virtually non-existent. The OWTT-iUSBL system will greatly facilitate Lagrangian experiments near topography, which are sorely required to improve boundary-layer parameterization in numerical circulation models and are also important, for example, in the context of larval dispersal and biogeography.

1.2 Hydrothermal Biology, Geology and Biogeochemistry

The mid-ocean ridge, a continuous geologic feature that encircles our planet, hosts hydrothermal activity in every ocean basins (Fig 3) [8]. Multiple Earth, Ocean and Life science processes are dependent upon this venting, but vary systematically along the ocean conveyor and/or according to varying ridge type, giving rise to hypotheses that remain to be tested.

Biologically, more than 600 species, new to science, have been found to be endemic to chemosynthetic ecosystems found at vent-sites, with an average rate of one new species every 2 weeks sustained over the past 30 years – a rate that was sustained through the end of the recent Census or Marine Life (CoML) decade [105, 42]. Clearly, many more vent-endemic species remain to be discovered. Indeed, discoveries made under CoML also led to entirely new biogeographic provinces (e.g. [84]). However, in the South Pacific, we still cannot assign a species richness value across vast tracts of Earths largest ocean basin [42]. From an *Earth Sciences* perspective, slow ridges are the most geologically diverse forms of spreading center hosting comparably diverse styles of venting

[40]. Recent work has shown that some such vents give rise to abiotic organic synthesis relevant to the origins of life (e.g. [72]) and, simultaneously, host both the volumetrically largest and the most gold and copper rich seafloor massive sulphide mineral deposits [41]. Recently, the GEOTRACES program has revealed how fluxes from hydrothermal systems could impact global-scale *Ocean Biogeochemistry*, [45, 83]; however, we lack understanding of how hydrothermal inputs to the ocean along the thermohaline conveyor. This is critical because, while dissolved Fe dominates the impact of venting on trace element ocean chemistry [40, 45, 83], the fate of that dissolved Fe varies as a function of the redox poise of the oceans along the thermohaline conveyor [29, 96]. By contrast most of our current global-scale models are predicated on the more detailed understanding that has come from decades of focus upon one specific site during the Ridge 2000 program at the fast-spreading East Pacific Rise. What is now recognized is that most undiscovered vent-sites lie along slow-spreading ridges in settings that are both far more abundant and more diverse than those already known from fast-spreading mid-ocean ridges (Fig 3) [10, 41]. Given their important mineralogical and biological resource potential, coupled with their potential to regulate ocean-scale biogeochemistry, we must improve our ability to locate and constrain the abundance and distribution of these still-unknown hydrothermal fields along the slow-spreading half of the global mid ocean ridge system much more efficiently than before. Further, at increasingly high latitudes and greater remoteness from traditional research nations ports, those future approaches must minimize use of conventional research-ships and rely increasingly on autonomous robotic systems.

The challenge of globally locating the diverse styles of venting throughout the Earth's oceans provides an excellent example of the impact of the proposed OWTT-iUSBL system on advancing ocean observation. While early studies suggested that vent incidence was predicted to scale linearly with ridge spreading rate [7], recent work (e.g., [41]) indicates that the partitioning of heat between different forms of hydrothermal flow varies systematically with spreading rate and, consequently, high temperature, mineral transporting venting may be much more common than previously anticipated along Earths slowest spreading ridges [10]. This implies that high temperature, mineral transporting venting may much more common that previously anticipated along Earths slowest spreading ridges [10]; however, the axes of these ridges are both broader than their fast-spreading counterparts. Hence locating all the diverse styles of venting present requires examination of a wider area of seafloor, across axis ($\sim$10km swath to span a rift-valley floor) and a larger depth-range of the water column — up to 1000m above the deepest point on the rift-valley floor [8]. The present best practice for ship-based investigations relies upon a CTD cast every 10km along axis to determine if venting is present, followed by multiple sets of along-axis tow-yos to identify the location of the plume source, typically to within 2-5km, prior to any AUV operations [47]. The slow pace of deeptowed operations (1.25 knots) implies that surveying $\sim$45km ridge segment requires $\sim$48h of dedicated shiptime, Furthermore, it is rare that any section of ridge crest is investigated for the presence or absence of venting and for a new vent site to be tracked to source on the same expedition [43]. Rather, it is typical for one expedition to determine if and where venting may be present and a second expedition, sometimes a decade later, to return and study that source (e.g. [46, 84]).

An autonomous observation system composed of a deep-diving AUG equipped with the proposed OWTT-iUSBL navigation system and an attending ASV represents a cost-effective (and perhaps the only realistic) method for undertaking these surveys. Using a Deepglider [78] equipped with OWTT-iUSBL to investigate the deepest 1000m of the water column would allow complete (inclined) vertical profiles along the relevant portion of a first valleys water every 3km along axis; triple the spatial resolution achieved by a research ship using conventional methods. Further, with an endurance of 150 days, a single well-navigated glider could explore 2800km of Mid Ocean Ridge in a single mission, equivalent to more than 12 months of dedicated shiptime [8]. Using multiple vehicles would further increase efficiency. If two or more vehicles conducted parallel surveys, offset vertically to intercept different portions of the water column at any given point along the survey, the spatial resolution achieved would approach that obtained from multiple simultaneous tow-yos, which is not possible from a single research ship. Finally, the long endurance capability of the deep AUGs envisaged, combined with advances in on-board autonomy and remote retasking would enable the adaptation of a survey strategy that enables an AUG to classify chemical anomalies in-situ, transmit them to shore upon resurfacing, and, because OWTT-iUSBL localizes these anomalies in the deep ocean to within a few hundred meters, the AUG could be retasked on the surface via Iridium to revisit that position for follow-on observations.

2 Proposed Research

The goal of this project is to design, build, and test — first in a test tank and then in the deep ocean — a new low-power external navigation system that can be accommodated on a broad array of widely-used underwater vehicles. One-Way Travel-Time Inverted USBL (OWTT-iUSBL) consists of a single source with access to GPS that periodically transmits to any number of subsea assets. A common time-base is maintained by chip-scale atomic clocks (CSACs) installed on all subsea assets (surface assets can use GPS time) that allow any vehicle receiving the acoustic packet to compare the time the packet was received with the time it was transmitted and compute a range to the geo-referenced location of the surface asset encoded within the packet. Array processing on the subsea asset yields an azimuth and elevation to the source that, combined with range, yield a stand-alone 3D geo-referenced position estimate. We envision early implementations of this system will employ a combination of an ASV serving as the source and AUGs receiving the messages; however, the small size and low power requirements allow this system to be installed on a wide variety of ocean assets—the acoustic source could be a buoy or fixed seafloor node while receiving arrays could be installed on Lagrangian floats, LRAUVs, or any other mobile ocean sensing asset. The system is likewise agnostic to the specific choice of ASV—a long-range slow-moving Wave Glider [69] as shown in Fig. 1 is an appealing candidate for similarly slow AUGs and floats, while fast-moving hydrocarbon-fueled ASVs would be more suitable for similarly fast AUVs.

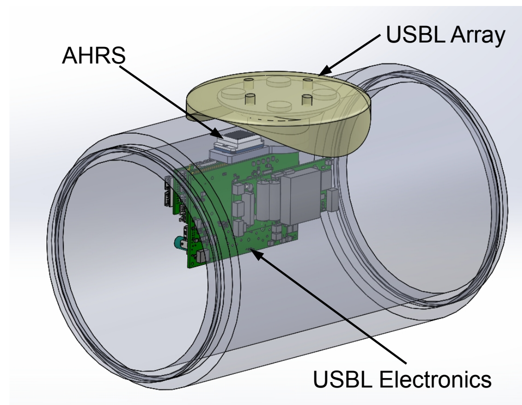

Figure 4: Concept sketch of the OWTT-iUSBL system installed in a payload module for a Webb Glider showing the key components — the acoustic array (sized for 10 kHz), attitude and heading reference system (AHRS), and the electronics including the chip-scale atomic clock (CSAC). The system will be designed to fit into a variety of low power deep submergence assets including the Seaglider that will be used in the project.

Fig 4 illustrates the design concept in the payload section of a Teledyne Webb Slocum Glider. The system contains three primary parts: *(1)* a four-element array capable of estimating the azimuth, and elevation of a received acoustic message; *(2)* an electronics package that includes the CSAC as well as signal processing boards and a microprocessor for on board computations (time-of-arrival and array processing); and *(3)* an attitude and heading reference system (AHRS) co-located with the array that compensates the raw azimuth and elevation measured by the array for the vehicle's attiude. All processing will occur within the system and a message with the estimated latitude and longitude will be transmitted to the vehicle's host computer. The system will be transferrable to a wide variety of mobile ocean assets, In this project we will integrate and test it on a 1000 m Seaglider [27], predecessor to the 6000m depth rated Deepglider [78].

2.1 Prior Work

The proposed system possesses certain advantages over extant acoustic navigation methodologies, chiefly: very low power requirements, no need for fusion with dead-reckoning or other navigation sources, and scalability to fleets of subsea assets with no degradation in performance.

Conventional inverted USBL (iUSBL) systems exist and are closely related to the proposed concept. In an iUSBL system, the transducer that originates the ping cycle and computes the range, azimuth, and elevation from the returned ping is resident on the underwater vehicle (rather than on the surface vessel) while the surface vessel has a transponder that replies when interrogated and encodes its position in the returned message [107, 52]. Commercial offerings are limited to the Sonardyne iUSBL family [50] and Benthos Directional Acoustic Transducer (DAT) [48]. The DAT is sufficiently low power (0.6 W receive) to permit its use on on small AUVs and LRAUVs [95] but lacks a precision time source, requiring the host vehicle to periodically expend additional power acoustically interogating a remote transponder.

The proposed system is related to, but has significant advantages over range-only one-way travel time (OWTT) navigation methodologies explored by co-PI Webster and others. Range-only OWTT navigation is reported in [53, 87, 25]; more recent work by Eustice et al. [28] reports a synchronous-clock acoustic navigation framework that employs Micromodems developed by co-PI Freitag [32, 31, 89, 37] in conjunction with low-power stable clocks. The system and associated distributed estimation algorithms permit individual vehicles to navigate themselves and other vehicles in a fleet using periodic inter-vehicle ranging. A number of navigation algorithms have been have been recently developed by co-PI Webster using range-only OWTT navigation [113, 115, 109] including recent successful use on Seagliders beneath sea ice [114].

Our proposed research is distinctly different from previous iUSBL and range-only OWTT work. Compared to iUSBL, our method eliminates the need for the submerged vehicle to expend the energy necessary to acoustically transmit and allows all submerged vehicles within range of the ASV to receive position updates at the same time—the proposed system reduces channel utilization by half for a single subsea vehicle and scales to multiple subsea vehicles with no penalty.

Our method also overcomes two limitations of range-only OWTT navigation. First, our method does not *require* fusing the acoustic data with dead-reckoned odometry (e.g., from a DVL/INS) to obtain a position estimate. Instead it provides stand-alone position estimates that can *optionally* be fused with dead-reckoned odometry for improved performance. Second, the method avoids imposing trajectory constraints on the subsea vehicle(s), surface vehicle, or both, that, when violated, can significantly degrade the solution or render the subsea vehicle position unobservable (e.g., [109, 36, 92]). Our method works for any number of vehicles whose horizontal positions are within approximately one water-depth of the ASV.

The concept of using an ASV to provide navigation aiding to a submerged vehicle is not unique to this work, but our approach offers certain advantages. Prior work includes: *(i)* the PIs' own work using range-only navigation [39, 66], *(ii)* work at Monterey Bay Aquarium Research Institute (MBARI) using a Benthos DAT [95], and *(iii)* work in the commercial sector using a commercial USBL system installed on an ASV and used to track a mapping AUV [4]. Each of these methods possess distinct disadvantages—*(i)* does not provide a explicit vehicle position but rather constrains vehicle odometery; *(ii)* requires the subsea asset to transmit a packet (thus consuming energy) and the subsea hardware is too large for use on gliders and *(iii)* employs a \$300k USBL system and also requires large subsea hardware. Furthermore, *(ii)* and *(iii)* are not extendable to multiple vehicles without reducing the frequency of position updates. In contrast, the proposed method is low-power (∼200 mW average, 700 mW peak), small, inexpensive (less than \$40k), and scales without performance penalties to multi-vehicle scenarios.

2.2 Feasibility Analysis

Analysis by the PIs demonstrates the achievable results of our proposed research concept and indicates a putative 1σ horizontal position accuracy of 30–300 m depending primarily on the attitude sensor used, the depth of the AUG or AUGs, and the horizontal distance between the ASV and the AUG. Furthermore, our results show an increased data collection efficiency for studies concerned with the water column above the seafloor to within a significant fraction of total water column depth. This latter result is surprising and significant in that the proposed system obviously

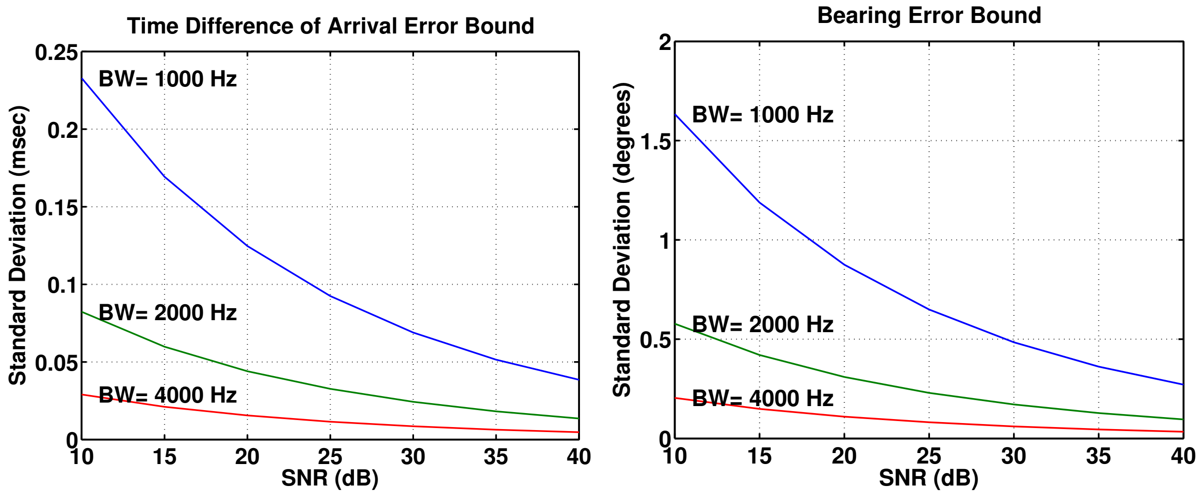

Figure 5: USBL array performance—time-of-arrival and bearing accuracy—versus signal to noise ratio in the 10 kHz band for various appropriate bandwidths (see text).

impacts endurance. The reduction in endurance is offset by increased time within the depth band of interest. Here we present analysis of the acoustic, navigation, and AUG endurance aspects of the proposed work. Navigation and AUG endurance analysis are extensively discussed in [58].

Acoustic Performance — Ultra-short baseline acoustic direction finding relies on measurement of time differences of arrival on two or more hydrophones. The accuracy of the derived bearing is a function of the noise of that time estimate and the length of the baseline. A convenient representation of the lower bound on time-delay estimation accuracy with respect to SNR, bandwidth and integration time is given in [21] (eq. 56b). Using representative parameters for bandwidth (1-4 kHz) and signal length (50 msec) appropriate for a coded signal such as an FM sweep or phase-encoded signal, the time difference error bound is shown in the left panel of Fig 5, and the resulting bearing error in Fig 5 (right). Advertised specifications for commercial systems such as those offered by Sonardyne (Yateley, UK) are cited in percent of slant range, for example 0.1% at 35 dB SNR [108] or 0.5% for the Sonardyne HF-8094. At 2000 m range the resulting location error is 2-10 m, which is bearing error of 0.05 to 0.3 degrees, corresponding roughly to the bearing error bound at 35 dB for broadband signals (2-4 kHz) as shown in the figure. For smaller arrays such as the Benthos DAT or the designs being considered here, the accuracy will not be as good, likely closer to 1-2 degrees [73]. Tank measurements using an array fabricated for WHOI by Material Systems Inc. (Littleton, MA) yielded approximately 1.5 degree standard-deviation for bearing using a four-element 2-D array, after calibration for systematic error. This results in 50 m standard deviation at 2000 m range.

Navigation Performance — All USBL systems including that proposed are subject to a certain set of error sources [51]: array accuracy as discussed above, the accuracy of array attitude measurements, alignment errors between the array and attitude sensors, and range and angular distortion from uncertainty in the sound velocity profile (SVP) (knowledge of the SVP enables compensating for these effects). In OWTT-iUSBL, the accuracy of the surface-to-vehicle slant-range measurement is also subject to error growth from the relative drift of the subsea clock; however, CSACs minimize this drift to $\sim 5.4\times10^{-4}$sec/day ($\sim$0.8m/day) — periodic resurfacing synchronizes clocks with GPS and zeroes this error. Table 1 in [58] lists the principal error sources for the proposed system along with specific values for the attitude sensors and other system components.

Figure 6 shows anticipated 1σ horizontal position error resulting from this analysis for the proposed system at 5000 m depth and equipped with one of three attitude sensors: a high-end north-seeking FOG, a mid-grade micro-electrical-mechanical systems (MEMS)-based attitude sensor, or a low-power MEMS-based attitude sensor with extremely low power (0.3 mW) sleep mode.

The figure illustrates some important aspects of the proposed system: (1) attitude error dominates for low-power platforms; and (2) errors are smallest directly beneath the surface beacon (where, fortuitously, acoustic performance is best and sensitivity to errors in sound-speed profile is minimized).

For the 5000 m depth case shown in the Figure, the OWTT-iUSBL system yields a putative 1σ horizontal position accuracy of better than 350 m at a horizontal separation of 5000 m (the figure for the lowest power AHRS considered). This is sufficiently accurate to collect observations in close proximity to dramatic seafloor topography (canyons, ridges, etc.). Unlike GPS, OWTT-iUSBL aiding is available at depth, providing a certain immunity to currents otherwise observable only upon surfacing. In contrast, a conventional AUG diving to 5000 m would accumulate navigation error throughout the profile and assuming, for the sake of comparison, 13.5% accumulated navigation error per unit distance traveled (the mean of four glider mission error reported in [22]), by the end of a 5000 m profile, AUG traveling at vertical and forward velocities of 0.066 m/s and 0.215 m/s respectively (typical of the Deepglider [78]) would accumulate ∼4,400 m of error — over 10x the error of our proposed system.

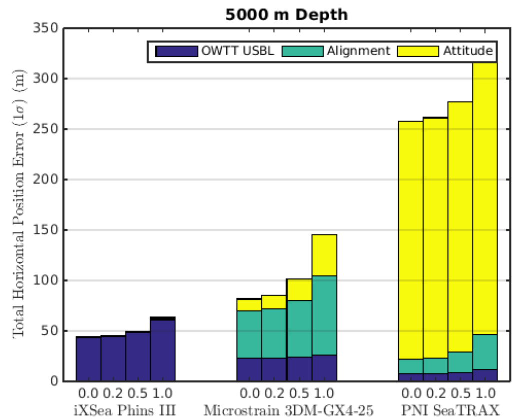

Figure 6: Single-fix error budget (1σ) for an underwater vehicle flying level at 5000 m depth. Each group of four bars represents a vehicle equipped with a particular AHRS (left-to-right, in order of decreasing precision and power consumption: iXSea Octans or unaided Phins north-seeking FOG; Lord Microstrain 3DM-GX4-25, and PNI Sensor Corporation SeaTRAX). Each bar within a group is labeled with horizontal range of the vehicle from the ASV, expressed as a fraction of total water depth. Each bar is split according to the percentage of the *variance* explained by each source of error.

This error stems from inaccuracies in AUG internal navigation (chiefly imperfect hydrodynamic modeling and compass calibration) and does *not* include additional motion imposed by subsurface currents. Indeed, the distance between the expected and the actual surfacing position is commonly used to estimate the depth- and time-averaged water current over the entire dive profile. The figure above applies to error in the expected position estimate (i.e. to navigation with zero current). A position error of 4,400 m results in a time- and depth-averaged water velocity estimate error of 2.9 cm/sec, and no mechanism, exclusive of adding a power-hungry on-board ADCP [103], exists to resolve depth-dependence (shear) nor time-dependence in subsurface current. External position estimates provided by the OWTT-iUSBL system would improve water current estimates in two ways: first, more frequent position updates will permit temporal resolution of current variations, and second, position measurements will occur throughout the profile permitting currents to be resolved by depth and shear to be quantified. The 2.9 cm/s figure above, which assumes noiseless GPS and arises from dead-reckoning error alone, is independent of time submerged and therefore represents a lower bound. However, current estimates derived this way must be applied as an average to an entire dive—potentially 1000s of m of water and 10s of hours (100s for deep-profiling). With OWTT-iUSBL aiding, it becomes possible to trade uncertainty in current velocities for improved spatial and temporal resolution. For example, current velocities binned into 1000 m thick layers and representing 4 hours of dive time can be estimated to within 50% of the lower bound (4.3 cm/s); 2500 m thick layers representing 10 hours of dive time to within 10%. These figures arise from naive application of the same methodology presently used with before and after-dive GPS fixes to pairs of OWTT-iUSBL fixes. Smoothing between multiple OWTT-iUSBL fixes or, for ADCP equipped AUGs, post-dive processing using stochastic state estimation (e.g., recent work by PIs Kinsey, Jakuba, and their students [75, 74, 94]) would further improve accuracy.

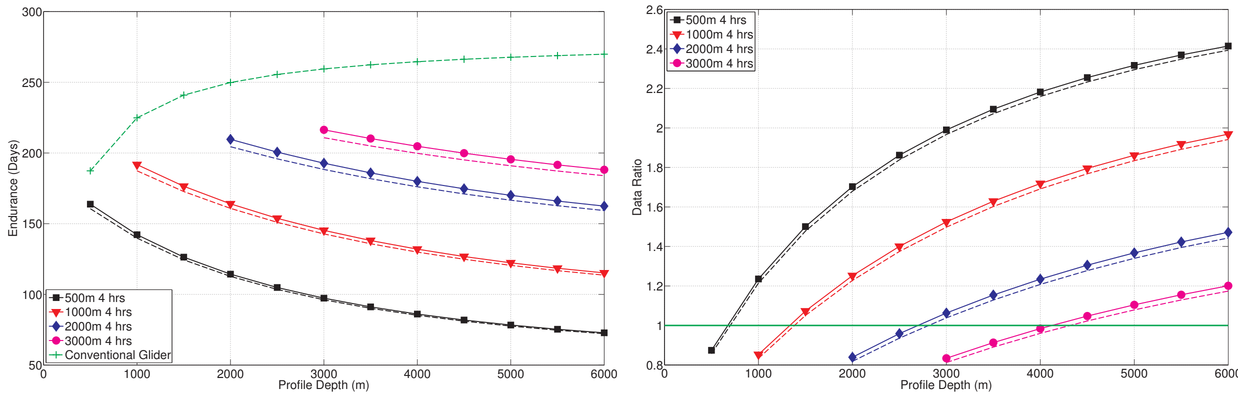

Figure 7: *Left:* Endurance of gliders performing conventional trajectories as well as deep-profiling trajectories. For the deep-profiling trajectories, four different profile heights are shown. Solid lines are for a OWTT-iUSBL update rate of 4 hours; the dashed lines are for a 10 minute update rate and indicate almost negligible impact (energy consumption is dominated by the increased pumping of deep-profiling, not the OWTT-iUSBL system). *Right:* The data ratios for an entire glider deployment. A data ratio greater than 1 indicates that the deep-profiling trajectory obtains more measurements within the desired depth band than a conventional trajectory despite the shorter deployment length. Originally published in [58].

AUG Endurance — The improvement in navigation afforded by the proposed OWTT-iUSBL system enables *deep-profiling*, in which an AUG undulates within a depth band defined by a profile depth and profile height (Fig 1). Additional analysis published in [58] studies the trade-off between endurance and volume of high-value data collected from within the depth band inherent to using OWTT-iUSBL when deep-profiling versus conventional un-aided profiling. Deep-profiling incurs two energy penalties that impact endurance: *(1)* the energy consumed by more frequent pumping, and *(2)* the power required to run the OWTT-iUSBL system itself. The analysis uses propulsion and hotel power numbers for the Deepglider [27, 78], and assumes the OWTT-iUSBL system is turned on every 4 hours and otherwise turned off except for the 150 mW continuous load of the CSAC. Knowing the total power consumption and the battery capacity (17 MJ), we can compute the total time a deep-profiling AUG spends in the desired depth band over the course of a deployment and compare this with the corresponding time for an AUG executing conventional profiles.

The left panel of Fig. 7 shows the mission endurance for a OWTT-iUSBL-equipped deep-profiling AUG in which it surfaces only every 5 days (the surfacing interval could be increased or decreased based on mission requirements). As expected, the increased power consumption reduces endurance; however, the ratio of time spent (or equivalently number of observations obtained) by the deep-profiling glider compared to a conventionally profiling AUG favors deep-profiling operations for a broad range of profile depths and heights (Fig. 7, right). AUGs executing profiles in narrow depth bands and/or at deeper depths will spend more time in the desired depth band and thereby provide a denser (and more synoptic) set of measurements in the region of interest. For example, an AUG executing 1000 m high profiles to a profile depth of 3000 m for hydrothermal localization along a ridge axis (Sec. 1.2) would have reduced mission endurance (145 days compared to 265 days for a conventional trajectory) *but would obtain 52% more data in the region between 2000–3000 m.* The ability of OWTT-iUSBL to increase observations in the deep ocean interior is not limited to a single AUG — accurately knowing where submerged assets are is necessary for autonomous multiple vehicle operations and enables new multi-vehicle observation strategies. For example, increasing the number of deep-profiling AUGs for a hydrothermal localization mission increases the amount and spatial density of observations obtained and enables AUGs to fly in close formation. An increase in the number of AUGs doing conventional un-aided profiles is less compelling because the ability to hold formation (without inter-vehicle relative navigation) scales with navigation uncertainty—from 100s of meters with the proposed system to kilometers.

2.3 Research Tasks

Task 1: Acoustic Array Design and Manufacture — We will design and fabricate a low-cost four-element acoustic array with direction of arrival accuracy that is appropriate for the intended use. The array design and manufacture will be done by BTech Acoustics, LLC, a local transducer design company. The proposed research represents a critical step toward what we anticipate will be the eventual commercial availability of an inexpensive USBL transducer suitable for widespread deployment on gliders and other deep-diving AUVs.

The proposed acoustic array builds on over 20 years of experience developing a variety of small stand-alone USBL acoustic subsystems, starting with an upward looking localization device for accurate tracking of a surface buoy with respect to a low-frequency acoustic receiver hanging 500 m below [33]. The array and processing algorithm were developed by Tom Austin (WHOI), the hardware was further developed into a homing system for the REMUS class of vehicles [56, 3] and remains in use on shallow-water REMUS-100 vehicles sold by Hydroid-Kongsberg. Co-PI Freitag worked with Austin on system integration and calibration of the arrays in the local ORE acoustic facility (now part of Edgetech, MA), and then developed a second-generation USBL receiver that was integrated into an early WHOI acoustic modem and used in multiple AUV homing and docking demonstrations [88]. In the late 1990s WHOI provided Benthos the same signal processing subsystems for an early version of their USBL product that was used on the European Marlin vehicle, and subsequently Teledyne-Benthos developed their own version that is conceptually similar, but utilizes a different processing approach [73]. The unit is sold as the Directional Acoustic Transponder (DAT), and it has been used in a MBARI vehicle, though not without considerable care in acoustic integration [95]. Over the past 10 years our USBL capability has been carried forward in the Micro-Modem line of acoustic communications systems [32], utilizing USBL arrays manufactured to WHOI specifications by Materials Systems Inc. (Littleton, MA, now part of Channel Technologies Group) and BTech (Fall River, MA).

Figure 8: Photo of elements of an acoustic array for navigation and homing designed by BTech in collaboration with co-PI Freitag. The four receiving elements are visible. This design serves as the basis for our proposed array.

As part of a recent deep-diving remotely operated vehicle (ROV) design project at WHOI, the development of an 11 km capable USBL for navigation and homing was identified as a risk, and BTech was hired to determine a design approach and perform a feasibility test (Fig 8). A simple pressure-tolerant design technique utilizing ceramic discs on a backing plate was evaluated by BTech and found to offer at least a 90-degree field of view, and this design will be the basis for the work proposed here because of its potential for a very compact implementation. The array will be mechanically referenced to the attitude sensor to minimize alignment error, and interfaced to a WHOI-developed multi-channel acoustic modem [37] where the signal processing to compute azimuth and elevation will be performed. The array design and initial fabrication will be done in the first year of the program, along with calibration in an acoustics test tank at the University of Massachusetts, Dartmouth, prior to at sea testing.

Task 2: Experimental Validation and Assessment — The performance of the OWTT-iUSBL system will be tested on the *Sentry* AUV during a proposed 7 day deep-sea cruise in Yr 2. The OWTT-iUSBL array will be mechanically installed on top of *Sentry* and we will take advantage of its water-column mobility and capability to rest on the bottom in order to test the accuracy of the navigation system. The primary objectives of the cruise are to: (1) validate basic functionality of the USBL array at a representative water depth; and (2) statistically separate the various error sources and quantify their contribution to the total error budget. Experiments (dives) will start shallow (∼1000 m) and incrementally progress to ∼5000 m.

Each experiment will have 2 parts. First, we'll use *Sentry* in a "lander" mode — i.e., the AUV will descend to and rest on the seafloor. This allows us to eliminate errors from dynamic vehicle motion. *Sentry* is equipped with a iXSea Phins-III north-seeking FOG and INS which we will use to attain ground-truth attitude and to detect any movement. The sea-surface acoustic transducer will be mounted rigidly to the ship rather than on an autonomous surface vehicle, to limit costs and simplify logistics. For ground-truth we will survey the vehicle on the bottom using the built-in ranging capability, and also take advantage of the Sonardyne USBL system that is part of *Sentry's* standard tracking capability.

During the experiments, the ship mounted transducer will repeatedly transmit from a fixed set of positions spaced evenly on rings of constant horizontal offset out to approximately two water-depths. Once this portion of the experiment is complete, we will drop *Sentry's* descent weight and execute a ∼4 hour mission during which we will observe system performance from a moving platform. The ship's lowered CTD will be used to measure the SVP approximately three times daily (during which the ship will be stationary but will continue to excite the USBL array). Dive duration will vary with site depth but in a 7 day cruise we expect to complete experiments at 1000 m, 3000 m, and 5000 m.

Task 3: Glider Integration and Field Testing — The OWTT-iUSBL array and instrument electronics will be integrated into a standard 1000 m-rated Seaglider in Yr 3. The OWTT-iUSBL array will be mounted on the upward-facing aft panel, leveraging existing designs for mounting an ECO Puck on the downward-facing aft panel (Fig 9). The array will be mounted such that it faces directly up when the glider is horizontal. Since a Seagliders typical glide angle is $\pm 15^o$, the array will be tilted fore or aft on descent and ascent respectively; however, analysis (Fig. 4 in [58]) indicates this will have minimal impact. The array will be interfaced to the main pressure housing using existing connectors for power and data, and the time of arrival, phase and angle measurements will be sent to the Seaglider host computer for logging and time-stamping with depth and other glider navigation information.

Testing will occur in three phases. First, the array will be installed on the Seaglider and a check of the calibration completed in a tank facility near WHOI. This allows confirming that the acoustic installation is clean and that any scatter from components of the glider will not impact the angle measurements. It also will ensure that the heading and attitude sensors are aligned with the acoustic array. Next, the system will be tested in in local waters near UW from a small boat with the glider doing normal (albeit shallow) dive profiles. A week of shallow-water work is planned to test the system prior to the cruise. The third and final test will be in deep water off the northwestern U.S., allowing full-depth, 1000 m profiles. Twenty-four hour operations are planned to collect data over multiple dives. OWTT-iUSBL positions will be computed in realtime and data will be logged on-board for post-dive analysis.

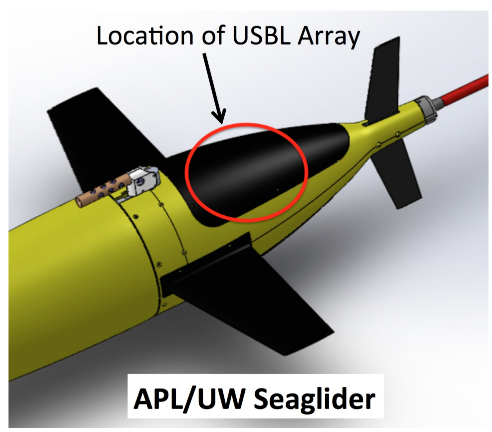

Figure 9: Model of the Seaglider showing the aft upward-facing panel where the OWTT-iUSBL will be installed.

An LBL transponder net will be deployed during the cruise to ground truth OWTT-iUSBL positions with a transducer already installed in the nose of the Seaglider initiating the LBL cycle and logging the returned travel times. The navigation data from the OWTT-iUSBL will be incorporated into the glider position estimate in post-processing, in order to assess both the equivalent real-time navigation performance as well as the best estimate, smoothed vehicle track and uncertainty. This will enable a complete comparison of the dead-reckoned (standard) performance, the range-aided performance, the OWTT-iUSBL-aided performance, and the ground truth from LBL.

Task 4: Synthesis, Reporting and Future Applications — We will synthesize results from the design, Seaglider integration, and at-sea testing and report them at the IEEE Oceans Conference and AGU Fall Meeting as well as publish results in the *IEEE Journal of Ocean Engineering*. Annual "all-hands" meetings will provide opportunities to summarize project results and discuss how future ocean observation missions might be conducted with this technology as well as identify any modifications required to achieve these missions. The interdisciplinary nature of our PI team (acoustics, navigation, and AUG engineers as well as a physical oceanographer and a marine biogeochemist) ensure a diversity of backgrounds contribute to this conversation.

3 Broader Impacts

The ultimate goal of this project is to provide a low-cost deep-ocean navigation system that is suitable for installation on a wide variety of mobile ocean assets and enables them to be paired with the growing number of ASVs available to the oceanographic community. We anticipate that OWTT-iUSBL technology, combined with existing and emerging AUG and ASV technologies will enable a wide variety of physical and biogeochemical processes deep in the ocean — examples include circulation [16], mixing [82, 110], and dense overflows [26], as well as the tracking of episodic events, such as plumes (e.g., [9, 19, 120]) and dynamic fronts (e.g., [119]), over long periods. The synthesis task (Task 4) is structured to help achieve this goal. Our collaboration with a commercial acoustic transducer manufacturer (BTech) ensures the array itself can be readily transitioned to commercial production at conclusion of the proposed work. The remainder of the proposed system consists of components already available through WHOI (Micro-Modem and CSAC carrier board) or commercial entities (CSAC itself and MEMS AHRS), plus the mechanical integration and software development that will be completed as part of the proposed work. We anticipate being able to tightly integrate the array and AHRS into a package mechanically and electrically compatible with widely used EcoPuck fluorometers (Fig. 4) in order to ease integration onto a variety of platforms.

Education and Outreach — The PIs have a strong record of engaging students at the high school and undergraduate levels and will continue these activities during this project using resources at our respective institutions. For example, WHOI hosts a variety of undergraduate summer programs, including the Partnership Education Program, the Guest Student Program, and the Summer Student Fellowship program, that allow undergraduate students to conduct oceanographic research in the laboratory and field. The PIs have previously advised numerous undergraduate students, and many of whom have contributed to publications [54, 106, 64, 39] and continued on to graduate school. These students had the opportunity to work directly with field robots and apply their engineering backgrounds to important ocean observation problems. During this proposal, we will continue these activities and provide opportunities for undergraduates to participate in field robotics programs. Our commitment to K-12 education is reflected in our continuing support of a program in which robotics and environmental science students at Natick High School (NHS) work collaboratively to design and build underwater robots that serve as platforms for the environmental science class to conduct experiments in local lakes in order to understand the impact of the local watershed on their community. This effort served as the foundation for NHS to successfully submit a proposal to the Lemelson Foundation to design and build a robot that in May 2014 was featured at the White House Science Fair. We will continue these synergistic activities over the course of this research project including participation in "lake work" days in which the environmental science and robotics classes work together to build technology for observing local ecosystems.

4 Results From Prior NSF Support

Kinsey (PI): NSF ANT-1126311 $1,996,965, 9/1/2011-8/31/2014: *MRI:Development of a Light-Tethered Undersea Robotic Vehicle for Seafloor Intervention in Ice-Covered Environments and Ship of Opportunity Deployment. Intellectual Merit:* Development of the *Nereid Under-Ice (NUI)* robotic vehicle for accessing the ocean beneath ice-covered seas and ice shelves. *NUI*'s unique unarmored fiber-optic communications-only tether enables a putative standoff distance of 20 km from a support vessel while under real-time human control, combined with on-board autonomy sufficient to return the vehicle to the ship for recovery in the event the tether is severed. *Broader Impacts: NUI* enables exploration and scientific access to under-ice and ice-margin environments that is otherwise impractical or infeasible using conventionally tethered remotely-operated vehicles. *Publications:* [15, 13, 116, 14, 12, 44, 60]. *Research Products:* Publications noted, the *NUI* vehicle itself, and scientific proof-of-concept data from field trials.

Freitag (Co-PI): OCE-0532223, $752,111; 6/1/2005-12/31/2009. *Acoustic Communications for Seafloor Observatories. Intellectual Merit:* We evaluated user needs, designed a complete multi-node acoustic communications system, constructed a prototype, and installed and tested it using the NSF-sponsored MBARI MARS node in Monterey Bay. *Broader Impact:* Developed and demonstrated a methodology for linking remote instruments to cabled infrastructure without cables, thus lowering costs and creating more opportunities for scientists to connect sensors to NSF-supported subsea networks. *Publications:* [30]. *Research Products:* Publications noted.

German (Co-PI): OCE-1344250: $800,000, 09/1/2013-08/31/2016: *INSPIRE Track 1: Collaborative Research: Transforming Remotely-Conducted Research through Ethnography, Education and Rapidly Evolving Technologies*. *Intellectual Merit*: This project seeks to expand the means by which scientists conduct oceanographic fieldwork. Research specialists in education and ethnography are working with ocean scientists to investigate better ways to use telepresence for both STEM-subject undergraduate recruitment and retention and enhanced access to the oceans from researchers working on-shore. *Broader impacts:* The project provides training for 6 early career scientists (two female), 7 UG students (4 female), 3 female co-PIs and 1 female post-doctoral researcher. *Products:* [38, 24].

Jakuba (Co-PI): NSF OCE-1333212:$859,790, 9/1/2013–8/31/2016: *Collaborative Research: An Autonomous Vertical Sampling Vehicle for Global Ocean Biogeochemical Mapping. Intellectual Merit:* Development of a fast vertical profiling autonomous underwater vehicle (AUV), called *Clio*, designed to cost-effectively improve the understanding of marine microorganism ecosystem dynamics on a global scale. *Broader Impacts: Clio* is intended to be a sampling platform that can be used simultaneously and independently of traditional wire-based sampling systems. *Clio* will lower operational and financial barriers to realizing an "-omics" global survey of marine genomics (DNA), transcriptomics (RNA), proteomics (proteins and enzymes), metabolomics (lipids and other metabolites), and metallomics (metals). *Publications:* The sampler and preliminary vehicle designs were presented at the American Geophysical Union Fall Meeting [57]; final design and fabrication is presently underway (Feb. 2016).

Thurnherr (co-PI): NSF OCE-1235094 ($1,356,952; 09/2013–08/16): *Collaborative Research: Flow, Turbulence and Mixing in Mid-Ocean Ridge Fracture Zone Canyons.* This on-going observational project investigates processes dominating the strikingly universal dynamics in ridge-flank canyons of slow-spreading mid-ocean ridges, where persistent along-canyon advection of density is balanced by high levels of diapycnal mixing. The project includes hydrographic surveys with CTD, LADCP and microstructure instruments, as well as deployment of a large array of moored instrumentation. The second survey was completed last fall and the moored instruments have been recovered. Data analysis is on-going, involving two post-doctoral researchers. *Intellectual Merit.* Preliminary results include i) close agreement of along-canyon hydrography with measurements from 1990s; ii) 2-layer along-canyon circulation; iii) several hydraulically controlled overflows at sills and narrows; iv) large overflow with persistent large unidirectional velocities and high levels of tidally modulated turbulence. Three publications (two led by post-doctoral researchers) are in preparation. *Broader Impacts.* Two post-doctoral researchers have been trained.

Partan and Webster (Co-PIs): No prior NSF support.

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