RESIDENT AUV

WORKSHOP 2018

May 9-11, 2018
Seattle, WA

Acknowledgments

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Citation:

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Executive Summary

Scientific Potential

Traditional ocean science technologies involve ships, satellites, submersibles, buoys, cycling floats, gliders, and solar or wave powered platforms. Lately, battery powered autonomous vehicles have become nearly routine. With this ensemble of assets, we have come to understand many long-duration processes operative throughout the breadth and depths of the ocean. As we learn more about the behavior of the global ocean and its use by human beings, a dominant theme emerges in the form of complexity. The intricate and intimate interplay among physical, chemical, and biological processes has occurred for nearly four billion years, creating an enormously complicated system for which we have little native understanding because the environment is hostile to human presence.

Working in concert, these processes have created, within a globally distributed fluid environment, a complicated suite of evolving, ever-shifting, four-dimensional marine ecosystems that, in the ensemble, function as the ultimate life-support system of our entire planet. To begin to fully understand this essential complexity, and to operate routinely, at will, within this environment, we must learn to be effectively 'present' throughout entire volumes of the ocean, for long periods of time, with the ability to make many simultaneous, coherent observations/measurements and to take co-registered samples, all indexed in time and space.

Yet, there is a class of processes within the ocean that are not accessible to us owing to current technical and operational limitations. These processes, both natural and anthropogenic, are commonly energetic, transient, and unpredictable. They are virtually impossible to examine with current technologies. Examples include, but are not limited to, major instabilities in methane hydrate deposits; erupting submarine volcanos; undersea mass-wasting events; fish and mammal migration patterns; 'thin-layer' development of phytoplankton and zooplankton; triggered turbidites; the ecological impacts of major earthquakes; episodes of anoxic and/or low pH (ocean acidification) upwelled waters in coastal systems; and timing of polynya formation.

Many of these phenomena occur deep within the ocean and cannot be readily detected, characterized, or quantified owing to the difficulty of anticipating the onset of such phenomena, and because of the practical intractability of launching the requisite assets in a timely manner in proximal locations to capture and thoroughly document such transient system-level phenomena. Furthermore, human generated events such as the Deepwater Horizon blowout took most by surprise and created an environment in which there were monumental technical challenges in both detection and remedial follow-up of the microbial response to the oil spill that might well have been facilitated by novel forms of autonomous instruments and platforms, which have changed dramatically over the last decade (*Scholin et al*., 2018). Yet many challenges remain to achieve a deeper understanding of the distribution, abundance, and activity of these highly diverse, marine microbial organisms. Recent advances in a range of instrumentation providing simultaneous in situ sampling of the water column over time and space could revolutionize the collection and analysis of all marine microorganisms.

Technologies providing both temporal and spatial coverage over depth profiles, across an eddy near the ocean's surface, or through an eruptive hydrothermal plume, will be essential to advancing our understanding of marine biogeochemistry (*Huber and Preston*, 2018). We must have the ability to sample the spatial and temporal variability and complexity of the environment in which microbes live, their role in it, and their response to ephemeral but important events such as submarine eruptions, oil spills, and harmful algal blooms. The integration of instrumentation that allows simultaneous sensing of co-registered environmental parameters, in combination with collection and preservation of filtered water samples for microbial analyses, are not readily accessible to the oceanographic community.

Beyond our planetary applications, persistent ocean-going autonomous robots will undoubtedly have a role in the exploration of off-planet oceans. The Earth's vast ocean will be a key testbed for systems designed to dive below icy surfaces to observe ocean worlds both within and beyond our solar system.

Workshop Focus and Key Findings

During the workshop in May 2018, nearly 100 participants from across academia, industry, and government agencies gathered in Seattle, WA, to assess the need for and potential of persistent mobile observing platforms capable of resident operations within ocean volumes of interest. Workshop participants divided into focus groups to consider resident autonomous undersea vehicle (R-AUV) use cases related to these four application areas:

- Mid-Ocean Ridges and the Overlying Water Column
- Gas Hydrates and Coastal Oceans
- Polar, Under-Ice and Off-Planet Oceans
- Maintenance and Operation of Installations

Despite the breadth of applications, the following technical elements emerged as clear common themes across R-AUV deployment scenarios:

- Power and data management sub-systems
- Communications
- Navigation
- Capable sensor and payload systems
- Advanced autonomy functions

The single most important conclusion of the entire workshop is that ***incremental technological steps toward realizing routine R-AUV operations could yield revolutionary scientific and operational value.***

Key findings:

- Participants in this workshop came together with the belief that the infrastructure required to routinely operate R-AUVs throughout entire volumes of the deep ocean is emerging as a crucial next step to support innovative, next-generation studies of complex, cryptic, rapidly evolving deep ocean processes or events that presently lie beyond our operational reach.

- Natural and many types of anthropogenic processes can be energetic, transient, and unpredictable, and often have potent, but unverifiable, consequences. Many such processes cannot be easily predicted, nor readily detected, characterized, or quantified owing to the difficulty of anticipating the onset of such phenomena and the depths and locations where they occur.

- The intractability of launching major sea-going assets with short lead times to capture and document such transient system-level processes from beginning to end means that our understanding of these and of derivative events is not readily expandable with currently accessible deep submergence tools.

- Long-term, persistent R-AUV systems, able to be deployed for months to years without support vessels, will have a profound impact on our ability to observe temporally and spatially changing phenomena throughout entire volumes of the ocean.

- R-AUVs may provide a means of remotely interacting with subsea infrastructure, offering tremendous savings on maintenance that would otherwise require staffed vessels and ROVs.

Each of the R-AUV subsystems necessary for resident applications have been demonstrated as viable, making persistent vehicular operations in the ocean a feasible next step. However, it will require investment in system engineering, integration, and testing efforts to truly make R-AUV operations become reliable and routine.

The spectrum of industry and academic participants in the workshop (see Appendix A) are evidence that industry–academic partnerships are likely to prove a powerful means of accelerating R-AUV system development and installations.

Existing cabled installations, including the Monterey Accelerated Research System (MARS) and the Ocean Observatories Initiative Cabled Array (OOI-CA), will serve as power and communications hubs for initial R-AUV installation and testing, due to their support of shore-based monitoring in real time as well as their proximity to dynamic natural phenomena. Alternative energy harvesting and storage technologies, and communication systems promise to provide flexible R-AUV operational hubs for deployment in ocean environments without existing infrastructure.

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Introduction

Resident AUV Concept

Autonomous underwater vehicle (AUV) capabilities have expanded the horizons of modern ocean science, driving new approaches to both mapping and observing the seafloor along with the variability in the overlying water column. Modern AUVs, able to operate autonomously while on-mission and underwater, still rely on manual intervention by a support vessel between individual missions. A major breakthrough in AUV operations will expand vehicular autonomy to encompass the full vehicle lifecycle, including unattended launch and recovery, automatic mission planning, response capabilities, and in situ recharging without direct human intervention. With this capability, future AUV systems will be able to reside at sites of interest, thereby becoming resident AUV (R-AUV) systems. In addition to the vehicle, the infrastructure of R-AUV system components (Figure 1) may include docking stations, power generation systems or cabled infrastructure, communications, and navigation devices. R-AUVs will complete multiple mission cycles over extended deployments and react in real time to unpredictable transient events without the need for costly on-site surface support, and will likely come to replace staffed vessel and ROV operations for routine inspection, maintenance, and intervention tasks.

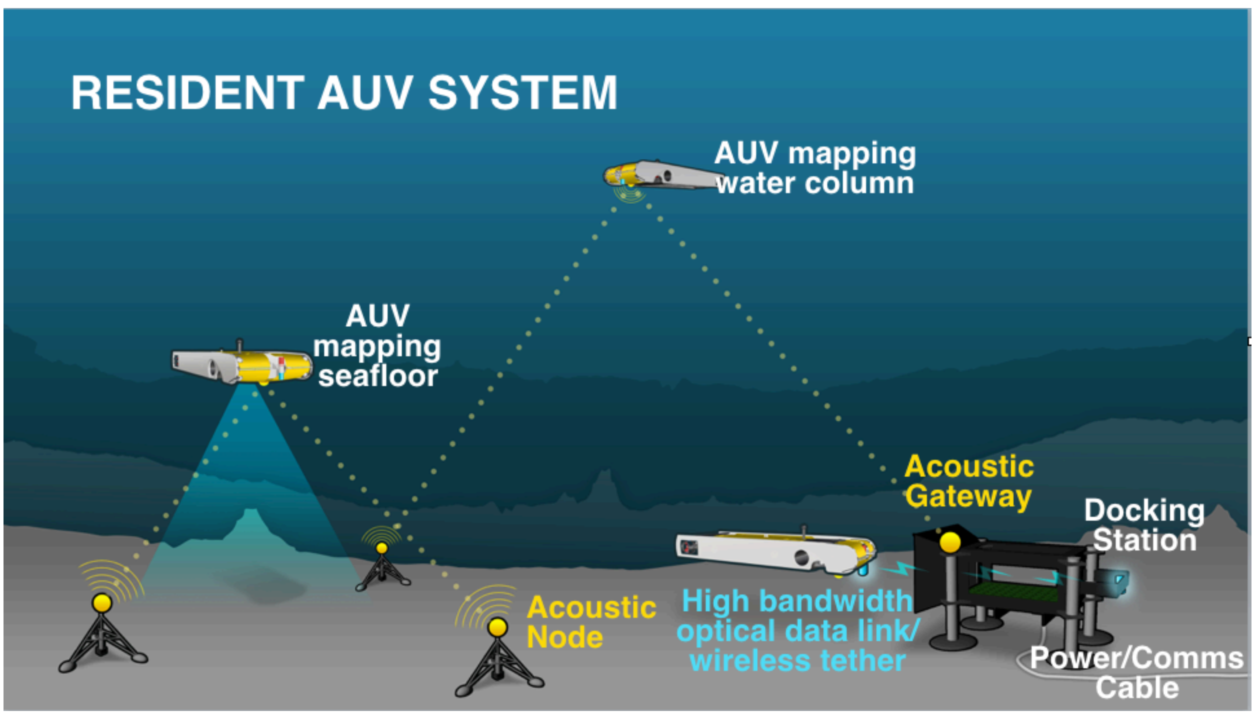


Figure 1. The overall concept and essential components needed for a R-AUV system. The power and communications chain starts at nodes connecting to land, and reaches one or more AUVs tasked with a wide range of potential missions. Such a system must incorporate real time or near-real time communications and the ability to recharge/refuel the vehicle, providing a means for routine or repeated operations, controllable from shore when necessary over deployment periods of months to years.

Decoupling the AUV from a support ship is a powerful concept, freeing the AUV from the financial, scheduling, and weather-related vagaries introduced by the operation of a surface ship itself. This advancement could open the door for deployments where the entire operational cycle can occur in situ with the vehicle ‘in residence’ at or near a site of interest. Having such a vehicle on-site allows novel four-dimensional sampling strategies to be defined remotely before, during, and after transient, dynamic events. Between events, a resident vehicle can perform regularly scheduled sampling and high-resolution (cm scale) mapping, imaging, and water column surveys, providing high spatial and temporal density sampling over long time periods. When a transient or dynamic event occurs, the R-AUV can re-task rapidly without the delays introduced by rescheduling and mobilizing assets from a distant port of call. After the event, an R-AUV can return to regular missions, supplementing its scheduled observations with adaptive measurements designed in response to the observed event.

Successfully developing a resident AUV system will require surmounting technical, financial, and operational challenges. The effort must be guided by one or more visionary goals, and backed by a strong financial commitment. Rarely do such highly technical systems function flawlessly on first deployment. However, there are two significant recent trends in ocean technology that make AUV residency in the pursuit of enhanced human–ocean interactions an increasingly achievable goal.

First, the completion and successful operation of the Ocean Observatories Initiative Cabled Array (OOI-CA) off the Oregon Coast, along with Ocean Networks Canada (ONC), the Monterey Accelerated Research System (MARS), and other global cabled observatories throughout the coastal oceans, have opened the door for a persistent, networked scientific presence in the ocean. By its very mission, the OOI-CA provides the power and bandwidth infrastructure necessary for recharging and communicating with a R-AUV. More critically, the OOI-CA provides a clear science mission, supporting the detailed three-dimensional, real time examination of Axial Seamount and proximal Juan de Fuca spreading zone from the seafloor to the sea surface. The potential of using a R-AUV to enhance the geophysical, geochemical, and biological understanding of mid-ocean ridge processes, including the overlying water column, is a powerful justification and a definable milestone.

The commercial subsea industry is increasing its investment in vehicle residency and autonomy to perform inspection and intervention tasks. In broadly distributed offshore deployments, both for conventional oil and gas extraction and for renewable technologies, R-AUVs promise a powerful cost mitigation against expensive vessel-based ROV operations for regular infrastructure inspection and service. Resident AUVs can be hosted on existing subsea infrastructure of a wellhead or wind turbine footing, and commanded from shore to perform necessary tasks without mobilizing a ship.

Similarly, the defense industry is increasingly interested in extending the reach of subsea assets, including AUVs, into dispersed or forward deployed, low observability, subsea deployments. Residency provides an ideal mechanism for a short-ranged asset to be deployed over the horizon, performing regular, sustained missions. While the defense and extractive industries have significant financial resources to invest in residency, we expect their interests to be defined sharply by their application-specific needs. Through active dialogue with these industries we believe common priorities can be established, allowing the science user community to benefit from their development investment, and similarly, allowing industrial users to benefit from advances in the science domain.

As cabled ocean observatories, industrial ocean installations, and marine hydrokinetic energy systems come online, there are an increasing number of power and communications nodes throughout the oceans with the potential of hosting long-term persistent vehicle operations. Test beds and early opportunities for R-AUVs will likely come in locations with existing power and communications infrastructure, including cabled ocean observatory systems like the OOI-CA, ONC NEPTUNE and VENUS arrays, and MARS. Therefore, the time is ripe for developing reliable, long-term systems capable of extended subsea operations.

This document describes the material presented and discussed at the ***Resident Autonomous Underwater Vehicle Workshop*** held in Seattle, WA, USA on 9–11 May 2018, and hosted by the University of Washington. With the purpose of exploring operational concepts and applications for R-AUV systems, the workshop focused on applications of persistent R-AUV systems for scientific inquiry. Participants collaborated to examine how adaptable, maneuverable systems with sustained remote presence can address critical science issues. Breakout groups evaluated use cases along the mid-ocean ridge, at gas hydrate deposits and coastal locations, in polar and off-planet regions, and for infrastructure operations and maintenance. Key operational concepts for R-AUV systems were identified for each application, including mission range and timing, desired baseline and adaptable behaviors, and compatible support systems. Summarizing the workshop findings, this report highlights both near-term and future scientific opportunities for R-AUVs, and reviews the necessary system capabilities and development steps to realize them.

Workshop Format

The workshop was organized over three days, with the intention of striking a balance between high-quality talks on relevant scientific topics and technology drivers, while leaving ample time for working groups to compile specific concepts on how R-AUV operations might look in their application(s). Over the course of the workshop, breakout group moderators guided the discussion through a transition from high-level science requirements to vehicle concept of operations and finally to R-AUV operational and component requirements. This top-down approach allowed participants to quickly identify key scientific questions on which R-AUV implementation would have the most significant impact, and to make progress towards defining R-AUV operations within the constraints of their chosen application area.

Communities Involved

Approximately 100 individuals, representing over 40 different organizations, including academic institutions, government agencies, and private businesses, attended the workshop, which encouraged cross-discipline coordination between scientists, engineers, and commercial technology developers.

Primary funding for the workshop was provided by the National Science Foundation, with additional funding from APL-UW and industry sponsor Modus Seabed Intervention, Ltd.

Discussion Groups

We organized ourselves into four major discussion groups addressing what were deemed four major scientific/environmental settings that are on the horizon for development. We recognize that these are not exhaustive, but we feel that they are diverse and representative of a broader spectrum of potential deployment scenarios.

Mid-Ocean Ridges and the Overlying Water Column

R-AUVs are particularly well suited to make the first quantitative observations and measurements of a major class of actively erupting undersea volcanos associated with the global mid-ocean ridge (MOR) system at Axial Seamount on the Juan de Fuca Ridge Crest off Washington and Oregon. The global MOR is nearly 70,000 km long, and portions of it lie beneath every ocean, yet never has the complete, very dynamic process of an eruption been evaluated directly in real time. Despite fixed cabled infrastructure and instrumentation installed at Axial Seamount during the last eruption in April 2015, the flux of energy and particulates released during eruptive events remains unmeasured because it requires a flexible mobile system, able to operate within the water column and adapt to the changing eruptive conditions.

Gas Hydrates and Coastal Applications

Most continental shelves (both active and passive) are riddled with unstable gas hydrate deposits that are actively, but intermittently, venting methane directly into the overlying ocean volume. This actively venting methane (25 times more potent as a greenhouse gas than CO_2) enters the deep ocean from sediments below in temporal/spatial patterns that are difficult to define and model. It is important to track the locations, timing, and amounts of methane release into the ocean–atmosphere system when it is released from underlying deposits. Continental margins the world over experience this type of volatile release activity, yet because it is both intermittent and irregularly distributed, it is difficult to map when and where it actually happens. Devoted autonomous survey fleets that can communicate in near-real time could provide a major step forward in this challenging and environmentally crucial arena.

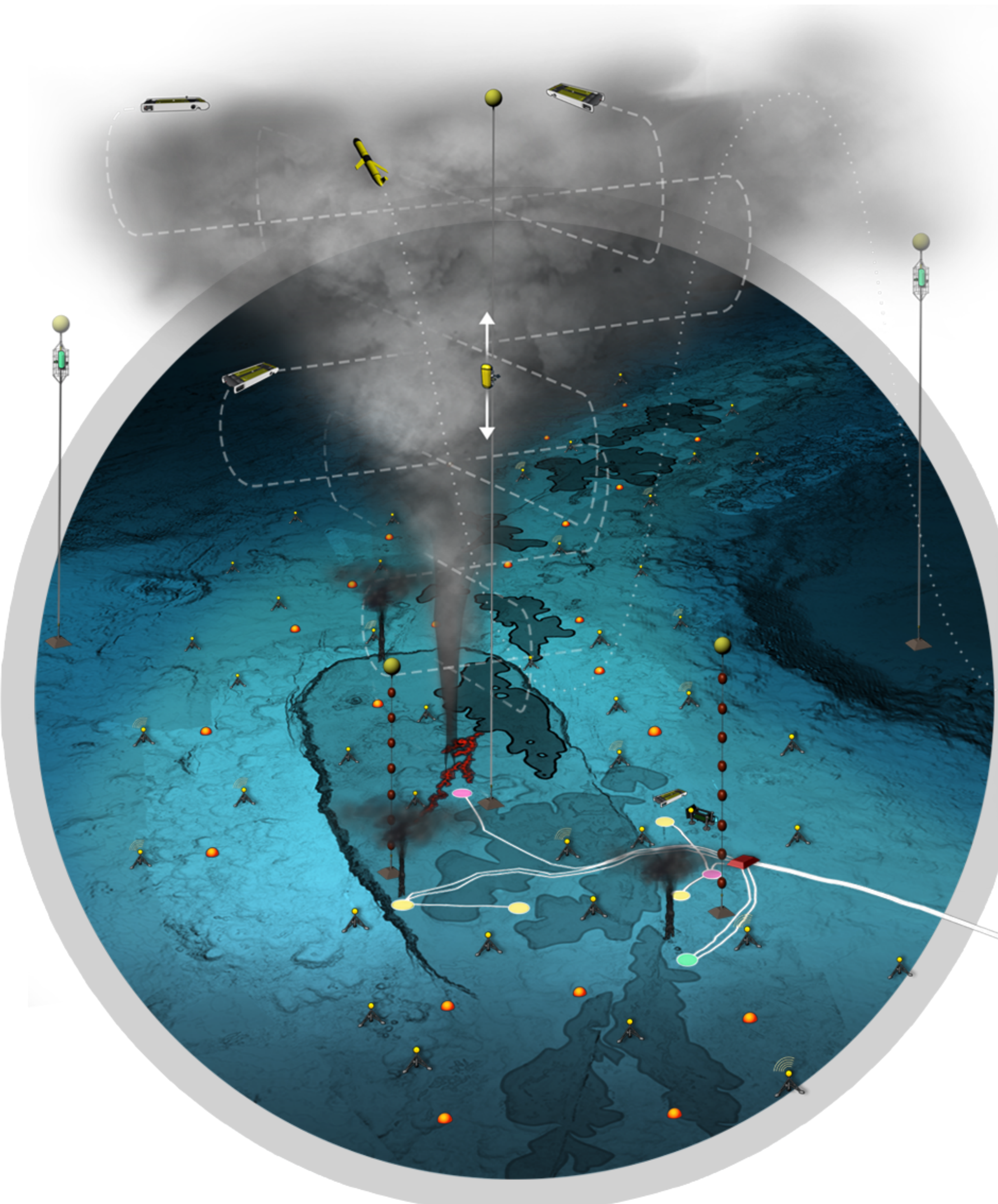
Polar, Under-Ice, and Off-Planet Oceans

With current technology, under-ice oceans on Earth have been found to be as productive as they are difficult to study. Major progress is being made in terms of assessing and evaluating the myriad interactive processes operating below ice cover in the many polar regions. Innovative designs of both performance and form factors are emerging to specifically target exploration of this challenging environment. In the longer term, many believe that there are off-planet oceans beneath ice cover (e.g., on moons of Jupiter and Saturn) that are likely to combine both volcanic activity and the potential of extant, indigenous life forms of considerable interest to scientists and society. Combinations of strategies developed to study actively venting hydrothermal systems deep below ice cover may become the leading edge in the search for life beyond Earth as our space programs learn to adapt novel systems designed for use on Earth to be robots for exploration of other oceans in the solar system.

Maintenance and Operation of Installations

A host of industrial and military uses for deep-sea platform autonomy, sensing, and communications are evolving continuously and rapidly. We captured some of the dialogues that took place in our workshop that were devoted to these types of issues, but understandably not all dialogues in this competitive arena were as candid as they were in the scientifically oriented discussions, owing to the nature of the industries and national interests involved. Industry participants contributed what they felt was germane, but not privileged, and departed with insights freely shared by academic and government contributors.

This report compiles working group output with outcomes, group exercises, and discussions. We have tried to provide parallels across each of the four main applications areas, but we reserved some latitude to allow for specific directions and interpretations of each working group.



Mid-Ocean Ridges and the Overlying Water Column

A Resident AUV at Axial Seamount:
To document and quantify mid-ocean ridge eruptions and their impacts on overlying oceanic ecosystems

A Perspective on Mid-Ocean Ridge Research

Over the past 43 years, since the discovery of submarine hydrothermal systems in 1977, mid-ocean ridge (MOR) research has been immensely productive as more than 300 active volcano–hydrothermal systems have been discovered along much of the 70,000-km length of this planetary-scale feature that is present in every ocean (*Beaulieu et al*., 2013).

Major insights gained in the past four decades include:

- The powerful nature of undersea eruptions and the large plumes they eject into the overlying water column
- The ever-changing nature of spreading-center environments including migration of molten rock into and out of crustal magma chambers, with its profound consequences for active hydrothermal systems and the exotic life forms they support
- Chemical–biological linkages in vent fluids, such as variable carbon and nutrient concentrations, and dramatic salinity shifts in effluents capable of supporting wide ranging microbial–viral communities
- Access to a broad spectrum of chemosynthetic, hyper-thermophilic microbial communities heretofore inaccessible for investigation
- The discovery of an extensive, deep, hot microbial biosphere extending well below the seafloor

These, and other exciting developments, have been gleaned from a host of submarine volcano–hydrothermal studies implemented over the past four decades by researchers from many countries working across the spectrum of MOR environments in the global ocean. Despite our amazing progress during these decades of research, studies of subsea MOR systems have had difficulty achieving certain objectives, such as:

- The ability to consistently study all facets of a single volcano–hydrothermal system over sufficient lengths of time (decades) to identify and quantify the significant interlinked changes
- The capability to know continuously, and in real time, the totality of interactive events that are taking place as entire systems evolve slowly or change rapidly
- The opportunity to launch immediate responses, within minutes to hours, involving imaging, sampling, and mapping, and in situ analytical activities to characterize directly all significant changes in these highly dynamic eruptive systems

- The ability to quantify processes and products of the transient events involved
- The capability to model, even in a rudimentary sense, the linked dynamic and energetic elements of the system from magma filling a chamber to zooplankton grazing on the top of an eruptive plume

Each of these items and a host of other objectives were addressed through the deliberations during the *NOVAE 2015 Workshop* (20–22 April; novae.ocean.washington.edu/story/About). Participants reviewed and integrated the disciplines involved in understanding the major processes in volcano–hydrothermal systems. Discussions led to plans for exploring the next-generation capabilities, experiments, and novel technologies on the horizon. A key goal of the NOVAE workshop was to generate and capture for later distribution and refinement the community strategies and approaches that will best capitalize on the existing and expansion opportunities of the OOI-CA natural laboratory at Axial Seamount (Figure 2). One recommendation from this workshop was to develop long-range AUV capabilities to track plume events in three dimensions.

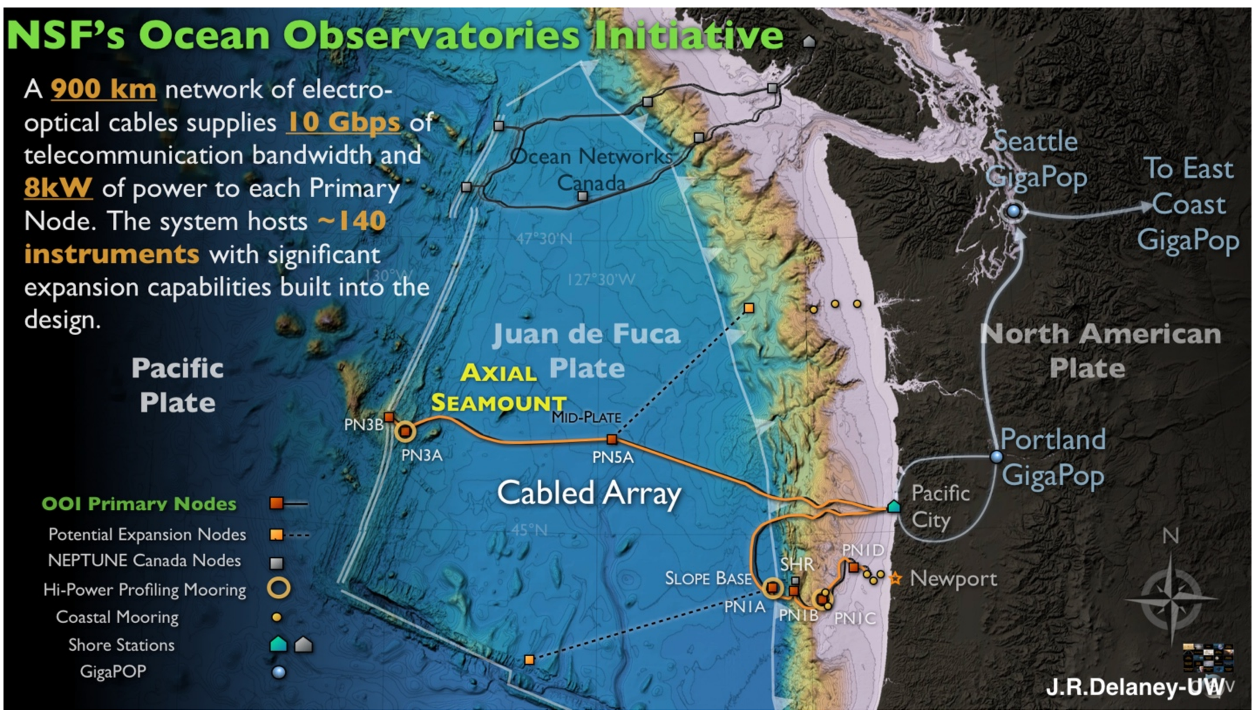


Figure 2. Stretching across the Juan de Fuca tectonic plate, the OOI-CA is a 900-km network of electro-optical cables that supplies up to 10 Gb/s bandwidth and as much as 8 kW of power to each of six primary nodes (red squares). At present (2019) the system hosts more than 148 instruments; the cabled array was designed to support significant expansion potential and could host a R-AUV docking station.

Axial Seamount Science: Background

Axial Seamount is one of the most exciting parts of the OOI-CA. Located on the western edge of the Juan de Fuca Plate and at the summit of a shallow portion of the Juan de Fuca spreading center, Axial is the locus of a highly active volcano–hydrothermal system (Figure 3).

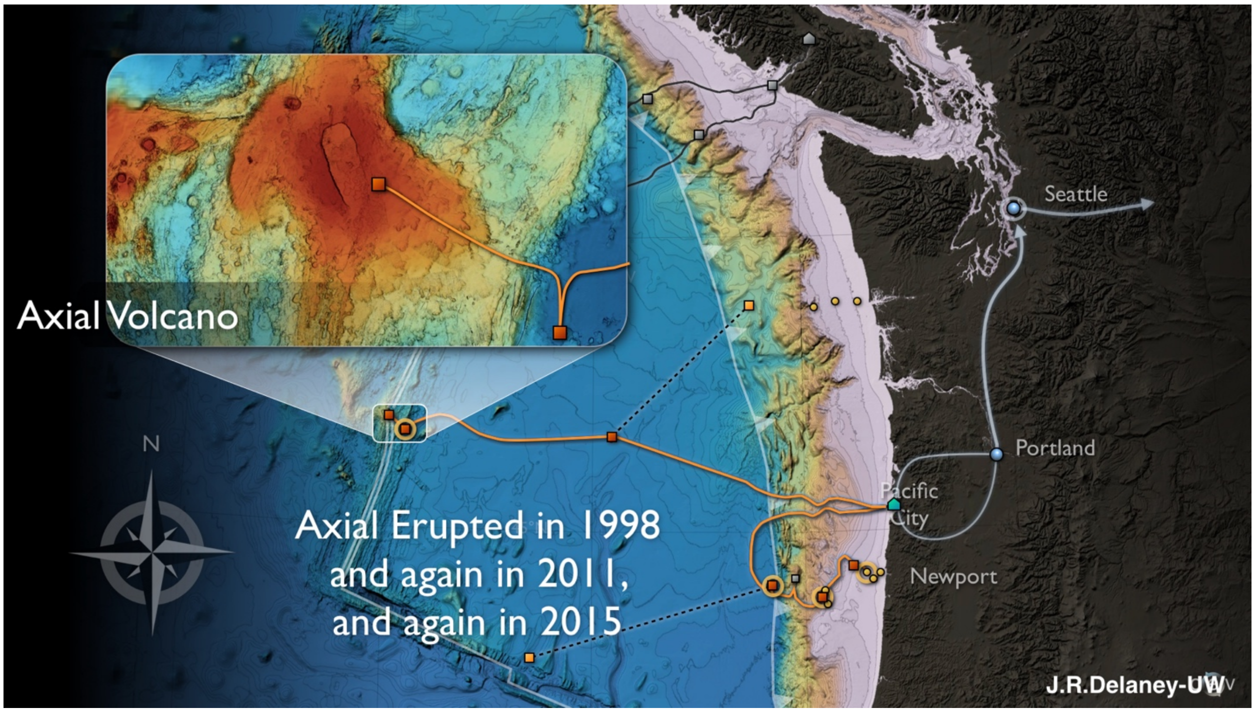


Figure 3. Axial Seamount (inset), an active volcano, is located at the intersection of the Juan de Fuca spreading center and the Cobb–Eickelberg Seamount chain. It represents an enhanced magmatic output compared to portions of the spreading center to the north and to the south. Axial has erupted at least three times in the past two decades, and it is likely to erupt again within 3–5 years. The OOI-CA extends across the plate to the spreading center, which bisects the caldera on top of Axial Seamount. More than 24 cabled instruments are distributed within the caldera; data flow continuously from them in real time to the shore and can be accessed via the Internet by anyone.

For several years, researchers (*Nooner and Chadwick*, 2016) had been monitoring the inflation and deflation of Axial Seamount using battery powered seafloor pressure sensors. Data were analyzed following recovery of the instruments. Following eruptions in 1998 and 2011, they documented inflation of the summit of Axial due to increasing pressure within the underlying magma chamber about 2 km below the seafloor (*Arnulf et al*., 2018). An especially exciting observation since 2012 by Arnulf and co-authors, was that the rate of rise of the caldera floor suddenly increased by a factor of four, from an average of 15 cm/year to nearly 60 cm/year at the center of the caldera.

Since 2014, with installation of the OOI-CA, the global community can now monitor the volcano in real time (Figure 4). There were 21 geophysical, geochemical, and biological sensors installed at the summit of Axial Seamount providing co-registered, live streaming data at unprecedented bandwidth. These include three cabled bottom pressure-tilt instruments built by Chadwick's group. Real-time data flow in 2014 to early 2015 showed unprecedented increases in inflation indicative of melt and volatile injection beneath the caldera.

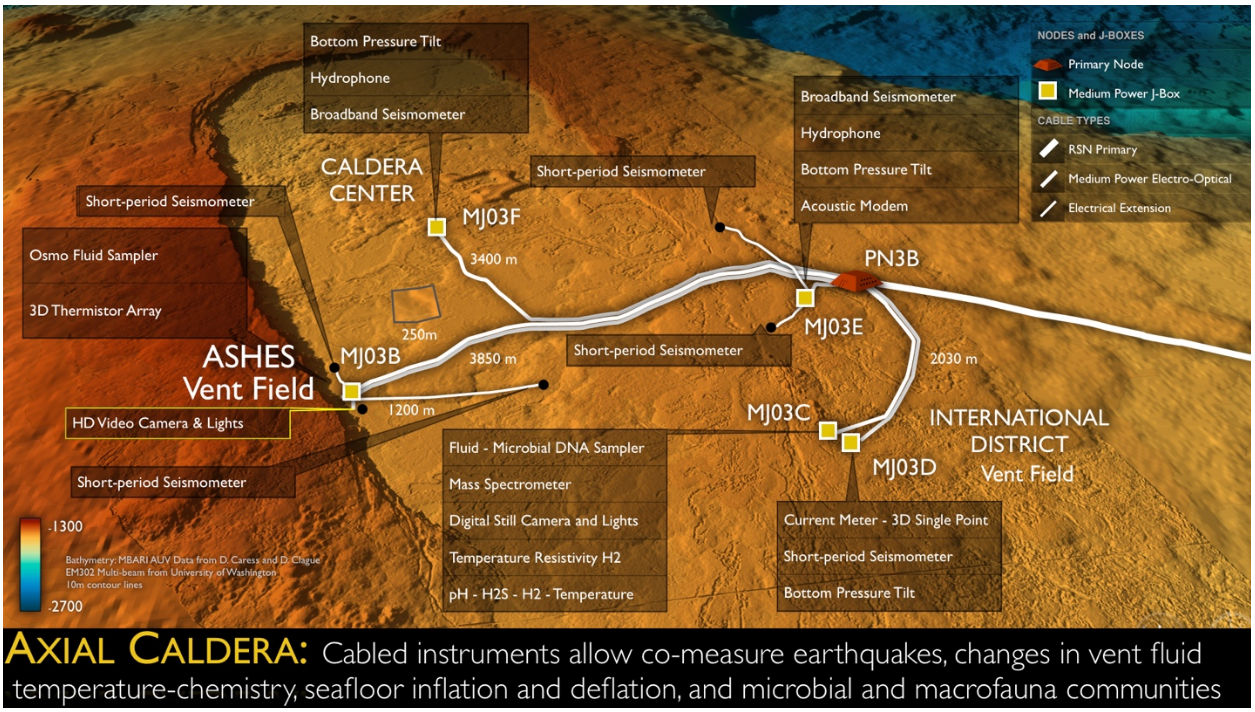


Figure 4. The OOI-CA system at Axial Caldera.

On 25 April 2015, William Wilcock, through hourly monitoring of seismic data from cabled seismometers on the volcano, communicated the following insight: "Quite a few earthquakes are now visible at the base of Axial, so I think this swarm is also more significant in terms of moment release." Over 8000 earthquakes were detected over a 24-hr period, and during this time interval the bottom pressure-tilt instruments showed that the seafloor dropped >7 ft; we concluded that the volcano was erupting! For the first time, scientists from across the country 'watched and heard' an underwater volcano erupt live from >300 miles offshore and nearly a mile beneath the ocean surface. Hydrophones detected implosive events that are interpreted to result from the explosions of pillow basalts as they are extruded onto the seafloor (*Tan et al*., 2016; *Wilcock et al*., 2016; *Caplan-Auerback et al*., 2017).

During the Cabled Array VISIONS'15 August operations and maintenance cruise, the area of hundreds of the impulsive events on the northern rift system of the volcano was visited and workers discovered recent volcanic output and minor hydrothermal activity. A bathymetric difference map documented a > 400-ft change in elevation of the seafloor, equivalent to two-thirds the height of the Seattle Space Needle. During a follow-on dive, with the robotic vehicle *ROPOS*, the science party saw the 3-month old eruption for the first time. Acres of microbial mats covered the summit of the new lava flow, fed by warm, volatile-rich fluids circulating through the thick lava flow.

Now, members of the science community interested in submarine volcanism and hydrothermal activity are remotely witnessing the complex processes leading up to an eruption, the actual eruption, and the transition from eruption to post-eruption. Scientists on land and instruments on site are capable of two-way communication at the speed of light (lasers on optical fiber) through connection to the Internet. This is an entirely novel opportunity for scientists and the public alike to observe the prelude, event, and denouement of the next Axial Seamount eruption.

The Cabled System to Axial Seamount

The most scientifically diverse and technologically advanced component of the Ocean Observatories Initiative involves 900 km of electro-optical fiber, extending from Pacific City, OR, across active portions of the Juan de Fuca tectonic plate, and upward into the overlying ocean. Completed in 2014, on time and under budget, this network enables real time, high-bandwidth, two-way communication with seafloor and water column sensor arrays across the Cascadia accretionary prism, the Juan de Fuca spreading center, and portions of the overlying Northeast Pacific Ocean.

Oceanographic processes in coastal environments, the California Current, and 400 km offshore are captured by six remote-controlled, profiling moorings covering full ocean depths. In August 2015 all sections of cable, all six operational primary nodes, all 17 junction boxes, and 97% of all 146 instruments were transmitting data ashore to the Internet via the Pacific Northwest Gigapop (http://www.pnwgp.net/).

In 2015 community requests to access seismic and seafloor deformational information for assessment of progressive inflation at Axial Seamount (*Chadwick et al*., 2012) resulted in NSF releasing, through IRIS (www.iris.edu/hq/), real time data from seven seismometers and three pressure sensors. At the NOVAE meeting on 20–22 April, 90 participants covering the spectrum of ocean sciences met in Seattle to explore scientific responses to an Axial eruption (novae.ocean.washington.edu), which actually occurred a few days later.

On 24 April, seismic event counts rose dramatically to many hundreds/hour (*Wilcock et al.*, 2016), the Axial caldera floor dropped 2.4 m in ~16 h (*Nooner and Chadwick*, 2016), and water temperatures in the caldera rose slowly by ~0.7°C, then declined in three weeks to normal values. Unusual waterborne acoustic signals indicated ongoing seafloor activity along the rift zone extending north from Axial. Seafloor mapping indicated new lava in that area (*Karson et al.*, 2015). Internet access to events far offshore began allowing interactive responses to complex processes unfolding within our ocean.

Capturing the Next Eruption at Axial Seamount

Volcanism and hydrothermal circulation along the 70,000-km-long global MOR system are major mechanisms by which the Earth's mantle has interacted with the ocean for at least the past 3.8 billion years. Hundreds of MOR hydrothermal systems have been identified and many tens have been studied in all the ocean basins. But the transient, powerful MOR eruptions are rarely detected, and have never been well studied. This is partly because they are far from land, they are commonly covered by ~1–4 km of seawater, and the eruption plumes reach neutral buoyancy well below the sea surface and therefore are not easily detected. Ship-based expeditions to assess submarine eruptions are rarely effective owing to innate mobilization delays that ensure the rapidly evolving eruption is well advanced, or even finished, before investigators can arrive on site with expensive surface ships and complementary deep submergence assets like a submersible or a remotely operated vehicle (ROV) at a combined cost of $80–100K/day.

The impacts of MOR eruptions on the overlying marine ecosystems are essentially unknown. Within days to weeks of the eruptive onset, we infer that rapid and massive injections of chemical, particulate, and thermal fluxes, as well as exotic sub-seabed microbial organisms, are launched into the overlying ocean. But these fluxes and the mechanisms by which they interact with and eventually disperse into the overlying or adjacent ecosystems of the open ocean are largely undocumented. Despite the lack of detailed knowledge about these eruptive phenomena, MOR volcanic eruptive plumes and hydrothermal vent plumes may be important sources of heat, chemicals, and microbes for much the surrounding ocean (*Butterfield et al*., 1997; *Holden et al*., 1998; *Baker et al*., 2012).

Conservative tracers of plumes (helium-3) may be detected up to 6,000–8,000 km away from the East Pacific Rise source (*Lupton*, 1998). There is some evidence that these eruptive plumes become eddy-like features that may be similar in behavior to the much better studied phenomena of so-called 'meddies', which are formed in the eastern Atlantic when masses of warm, salty water from the Mediterranean overflow through the Strait of Gibraltar into the ocean and spin up into Coriolis-driven, eddy-like boluses that retain their coherence for many months to years (*Iorga and Lozier*, 1999a,b). If this is a valid analogue to the water masses generated by eruptive plumes, they may alter both vertical mixing and the biogeochemistry of the deep ocean over large space and time scales. There are literally no data to evaluate this proposition.

Much of what we do know of the event plumes derives from the work of Ed Baker and his colleagues (*Baker et al*., 2012), who report at least three explanations for the source of the heat in the event plumes: 1) emptying of a crustal reservoir of hydrothermal fluid; 2) cooling of a lava flow and/or dike; and 3) sudden magmatic gas release. Clearly one of the outstanding issues revolves around how, and from where, do the event plumes get their energy and chemical signatures.

As captivating as it will be to determine the details of the seafloor and sub-seafloor events involved in the formation of eruptive plumes, the largest and most intractable scientific problem to be solved regarding MOR eruptions involves the most transient of all processes: the rapid release and subsequent dissipation of eruptive plumes into the water column with its unknown impacts on the ambient overlying oceanic ecosystems. Most of the effects below the seafloor can be increasingly well-resolved by judicious placement of seafloor sensor packages, such as seismometers, pressure gauges, and tilt-meters, along with other geophysical and geochemical sensors deployed on or near the seafloor in active zones.

However, the opportunity to interactively define the evolution of an erupting MOR volcano and its impacts on ambient marine ecosystems is finally within our grasp technologically. Axial Seamount is an active MOR volcano on the Juan de Fuca Ridge. It has erupted three times in two decades and may erupt again soon (*Chadwick et al*., 2016; *Wilcock et al*., 2016). Owing to the efforts of the NSF OOI-CA program, Axial is currently instrumented with arrays of sensors linked directly to the Internet and archiving systems by subsea electro-optical cables. This network provides interactive connectivity and electrical power to several tens of seafloor/water-column sensor packages located on and near Axial Volcano. By employing a well-configured and highly adaptable in situ R-AUV docked near the edge of the caldera on the summit of Axial we can use the electric power and unprecedented bandwidth of the OOI-CA to charge the R-AUV batteries and to transmit all data collected by the vehicle during its water column survey mode (Figure 5).

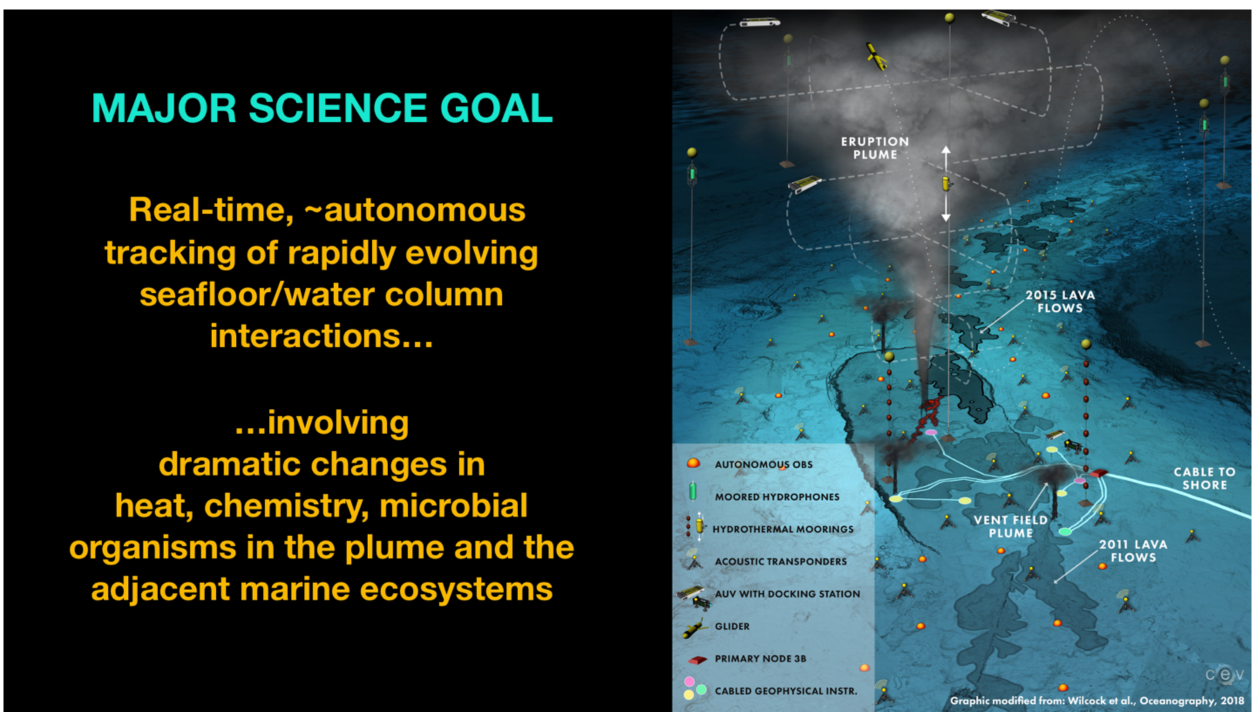


Figure 5. Artist's vision of the interactive examination of an eruptive plume at Axial Seamount. Conceptual rendering of an eruption on Axial Seamount with Sabertooth R-AUVs surveying the water column to define evolving dimensions, heat content, chemical and particulate load, and microbial signature of eruptive material, and its changing boundaries with the displaced pre-existing ambient oceanic ecosystems.

We propose that we will be able to interact with the AUV via cable from shore while it is in the dock, it will be re-programmable on-the-fly, and it would allow an adaptive response in real time to the onset and complete evolution of a submarine MOR eruption. All this can happen in concert with data flowing from supporting cabled sensors distributed across the seafloor and up into the water column. With appropriate sensors the R-AUV would be able survey an area about twice the size of the caldera, which is 3 x 7 km. It can also survey over the depth range (2000 m to 500 m) of event plumes observed previously. It would conduct detailed real time mapping and sampling of rapidly evolving eruptive plumes and their adjacent, marine ecosystems displaced by the injection of eruptive input.

At the end of a surveying mission, upon returning to the seafloor dock for battery charging, all recently acquired survey data would be uploaded via optical modems at the speed of light to cloud computing resources on land. Designated community experts would process all data in time to inform the next AUV mission following the 10-h inductively coupled charging cycle. With time, the artificial intelligence operating system would take on increased autonomy. Detailed seafloor documentation might have to await basic characterization of the more dynamic processes in the overlying oceanic portion of the system, as they are integrated into the models of eruptions that are running in real time on the cloud.

R-AUV Concept of Operations at Axial Seamount

Proposed Locations

The ideal locations for the docking station would be near the summit of the volcano in a location that is the least likely to be invaded by eruptive lava flows, but is near enough to the OOI-CA primary node 3B to allow effective operation and servicing.

Baseline and Event Response

There are three time domains in the response strategy for capturing and documenting the eruptive impacts. The first period is before the eruption, during which the vehicle would move through the volume of the water column that is most likely to be impacted directly by the eruptive releases (there may be more than one at a time). All the sensor systems that would be employed during an eruption would be in play and the survey would occur at a frequency of once weekly. All the data would be downloaded during the early part of the charging cycle and routed to a cloud computing setting, where investigators across the country could examine and perform quality assurance–quality control on the information gained. Then the ensemble would be rendered in an optimal visualization scenario that would inform the follow-on surveys. In this fashion the teams involved could test survey strategies and characterize the natural, pre-eruption variability of the overlying water column ecosystems in the volumes likely to be invaded by the eruptive plume.

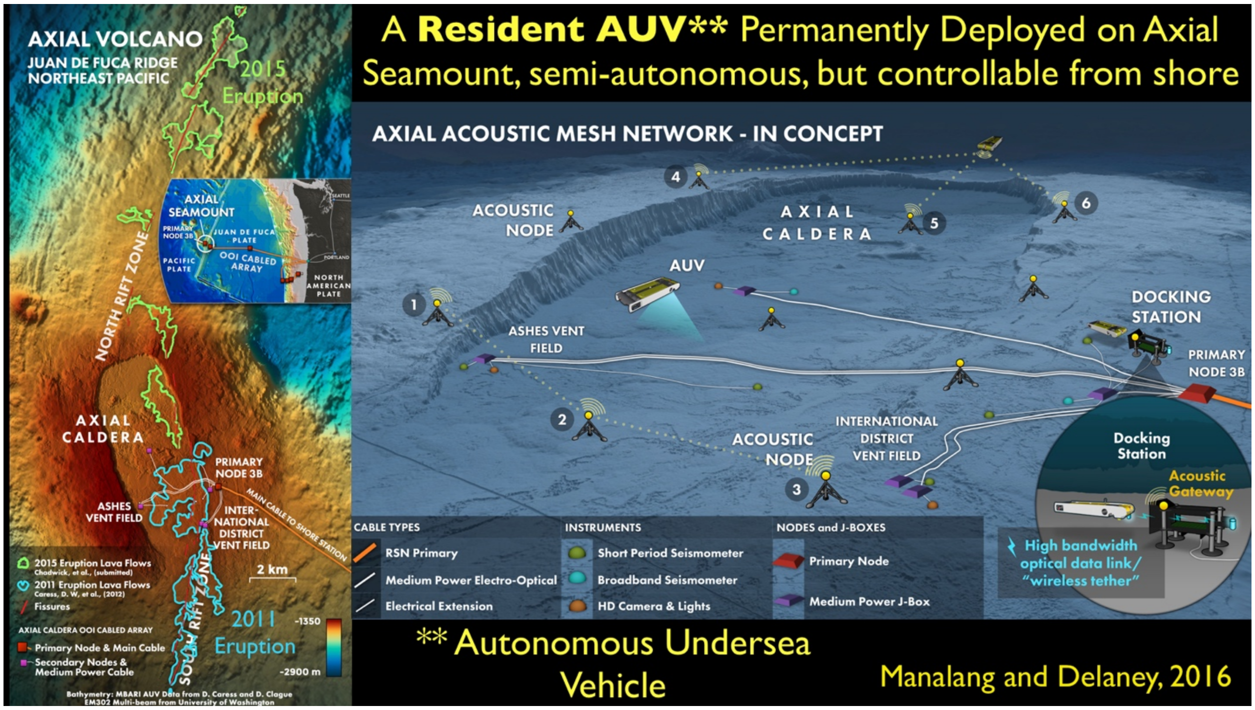


Figure 6. Existing and proposed infrastructure for Axial Seamount. *Left*: Map of Axial showing caldera. The 2011 lava flow (blue outline) and 2015 flow (green outline) are partially in the caldera. *Right*: A perspective image looking to NW. The caldera and the cabled sensor locations are in place. The docking station, the transponders, and examples of the Sabertooth AUV in the water column are shown.

The second major period involves the intense one to two weeks as the eruption is unfolding and plumes are forming in the areas most likely to be proximal to the caldera, although during the 2015 event, a series of delayed eruptive activity occurred as much as 10 km north of the caldera along the rift zone. The operation would swing into high gear at this point and the survey–battery charging cycle would become the determining factor in what can be accomplished in terms of full survey coverage of the evolving plume. In each case, during the charging period the data would have to be processed and made available in an optimal visualization mode to guide the next water column survey mission. During the eruption we would signal a group of glider investigators who would deploy their gliders with the specific objective of seeking out the known location of the plume while it is still proximal to its eruptive source, then the gliders would track the evolution of the plume or plumes as they migrate away from the source area. Fluid sampling of the plume waters and the surrounding waters for eDNA would commence as early as possible.

Once the eruption has ceased and/or the plume formation has decreased substantially, the gliders would begin tracking the plume and the AUV would devote its time to thoroughly characterizing the near seafloor activity, which would consist of mapping new lava flows and mapping, photographing, and sampling known and new venting sites.

Sensor Selection

Several approaches for operations were discussed. To support the diversity of science questions, the recommended suite of sensors and their measurements can be divided into science sensors and engineering sensors.

Science:

- Multibeam sonar
- Side scan and sub-bottom sonar
- High-definition camera
- Multifrequency bioacoustics
- Conductivity, temperature, depth
- Dissolved oxygen
- pH
- Methane
- Oxidation reduction potential (ORP)
- Turbidity

Engineering:

- Inertial navigation system (INS)
- Doppler velocity log (DVL)
- Sound velocity
- Depth
- Attitude (pitch/roll/yaw)
- Forward-looking sonar (obstacle avoidance)
- Acoustic modem/navigation beacon
- Optical modem

Other science instruments, such as stereoscopic video imaging, an Environmental Sample Processor (ESP), and iron, manganese and water samplers were also recommended. Due to the number of sensors needed, participants suggested that the project either have two R-AUVs deployed at Axial at any one time, one for seafloor measurements and one for water column measurements, or have suites of different sensors on separate sleds that could be picked up by one R-AUV as needed and stored at the docking station between missions to recharge batteries.

The R-AUV would need to survey in and around the caldera and on the outer flanks, as well as be able to do vertical profiles up into the water column to at least 500 m depth, which is estimated to be the upper limit of an event plume. It was also noted that biological impacts could be expected to be observed above the event plume at depths < 500 m. To accommodate this spatial range in missions, at least one docking station at the OOI-CA primary node is needed and possibly another docking station elsewhere to allow longer-range deployments. In addition, a system of navigation communication nodes is required around the caldera to allow the vehicle to navigate in the water column once it loses the seafloor signal.

Baseline and Event Response: Survey Sampling Strategy

Water column parameters need to be investigated during a 1-year baseline phase before an eruption, at a higher frequency during the eruption, and then less frequently during a 3–5-year post-eruption assessment phase to determine how temporal and spatial scales differ between event and non-event processes.

Baseline

Important water column parameters need to be assessed for at least one year before an eruption to establish a seasonal baseline, as well as define the composition and temporal variability of different chronic vent plumes. An evaluation of the frequency of surveys and various survey strategies still needs to be assessed. Survey patterns could include a lawn mower pattern, nested grid, star shaped, spirals, vertical profiles, and hovering over specific vents, etc. Water column parameters should be investigated relative to tidal cycles (e.g., 6–10 vertical profile samples in one day, monthly) and to evaluate other seasonal energetic circulation processes. A routine weekly three-dimensional survey over the caldera could be balanced with monthly surveys over the ring faults (caldera walls), monthly surveys near the seafloor at specific vent sites, and specialized investigations to capture specific events, such as a flux event from a spring bloom. A 20-km sampling range would be optimal and should be surveyed at least once monthly. When seismic activity starts to increase (about two months before the 2015 eruption), the R-AUV battery must be maintained above 50% power, ensuring rapid response.

Eruption

After finding the location of the eruption source using the seafloor packages, the R-AUV will survey the water column to find and define the edges of the plume. The plume may not be co-located with the eruption site. Another suggestion was to use multiple gliders to define the spatial area of the event plume and then have the R-AUV map all parameters. Once the plume spatial area is determined, the R-AUV will conduct daily exploratory mapping and maintain flexibility to allow for adaptive sampling. Several predefined survey strategies, e.g., spiral survey to get vertical dimensions, should be agreed upon in advance of an eruption.

Seafloor

A baseline for seafloor topography of recent lava flows is already available (Bill Chadwick, pers. comm.). Seafloor mapping using a R-AUV will start as soon as seismic signals increase (order of magnitude), indicating an eruption event. To date the eruption has always started in the caldera, even if it later moves to an outer flank. New lava flows, explosions, and heat signals (3°C) can be used to locate the source. Three types of seafloor surveys are needed.

The first survey will remap the eruption site using multibeam and side scan sonars surveying at 70 m above the seafloor, with survey line spacing at about 100 m apart, maintaining 1-m precision and 5–10-m accuracy. Inertial navigation, Doppler velocity log (DVL) navigation with bottom lock, and acoustic updates will be required.

Additional surveys using a stereo video camera at 5 m above the seafloor will be conducted to collect images of bacterial mats and other hydrothermal vent communities and to collect fluid samples for chemical and biological composition of vent plumes (e.g., Environmental Sample Processor). Seafloor surveys will be repeated weekly to determine lava flow changes over time. Lava may continue to outflow at different locations for over one month and more than one plume may be generated.

Post-Eruption

Water column surveys will continue. Inter-annual sampling is needed due to the large variability at this temporal scale in water column parameters experienced at this site. For example, El Niño, the Pacific Decadal Oscillation, the warm Blob, and other decadal anomalies are important processes in this region. In addition, eruption plumes could advect >1 km/day. Recently developed deep gliders (3000 m; *Osse and Eriksen*, 2007) could be used to track event plumes off the ridge crest to investigate dissipation rates.

Complementary Assets to Enhance R-AUV Impact

It was recognized that an R-AUV is essential to advance understanding of event plume effects on the ocean environment. However, there are large risks associated with deploying a R-AUV as frequently as participants wished. Several options to support R-AUV activities are reported. It is also important to think carefully about how best to enhance the supporting infrastructure (both cabled and un-cabled) to ensure optimal use of the R-AUV system (Table 1).

Table 1. Recommended support infrastructure for R-AUV missions at Axial Seamount

Seafloor	
	More hydrophones (perhaps connected to cable by acoustic network)
	More seismometers (cabled/wired)
	Acoustic tomography array in water column
	Acoustic mesh network sensors (transponder modules from Sonardyne)
Water Column	
	CTD (redundancy and instrument stability)
	High-resolution inertial motion for flow velocity (geo-referenced)
	Multibeam sonar for early detection of plumes near the caldera
	Side scan sonar for lava flow definition and evolution
	Multi-frequency bioacoustics to sense plankton
	Dissolved oxygen
	Oxidation reduction potential
	Turbidity (optical backscatter to define plume edges)
	Environmental Sample Processor (DNA analysis)
	High-resolution, stereoscopic photography and video imaging
	Camera imaging for flocculated material, zooplankton
	Methane (current technology has slow response; development needed)
	pH
	Fe (micro-fluidic systems available from National Oceanography Centre, Southampton)
	Mn (under development)
	Water (dissolved gases and metals)

It was recommended that at least three moorings be deployed in addition to the R-AUV to provide continuous data to capture tides and low-frequency inertial motions that slow vehicles cannot provide. One cabled profiling mooring (to 500 m depth) should be deployed in the middle of the caldera and three autonomous moorings around the rim of the caldera. Mooring sensors should include temperature, salinity, dissolved oxygen, turbidity, oxidation reduction potential, and a 1200-kHz Nortek acoustic meter. The R-AUV could download the sensor data from the autonomous moorings and transfer the data to shore via the docking station. In addition, these fixed mooring sites are essential for model data assimilation.

Multiple deep gliders would be valuable to cover a larger spatial area, investigate chronic plume activity, and follow event plumes off ridge. A navigation network is essential to the R-AUV mission. Acoustic tomography could be used to detect a large change in the environment, as water density will change dramatically at eruption. Twenty acoustic tomography sensors could be deployed around the caldera to detect plume events and guide AUV sampling.

Another option discussed was to have anchored floats in the caldera that could be released during an eruption to help define the spatial variability of the plume. Having a robotic capability on the R-AUV was discussed. Robotic arms would allow the R-AUV to move the meshed network nodes to different vents to collect sensor data and physical samples and allow greater R-AUV spatial sampling.

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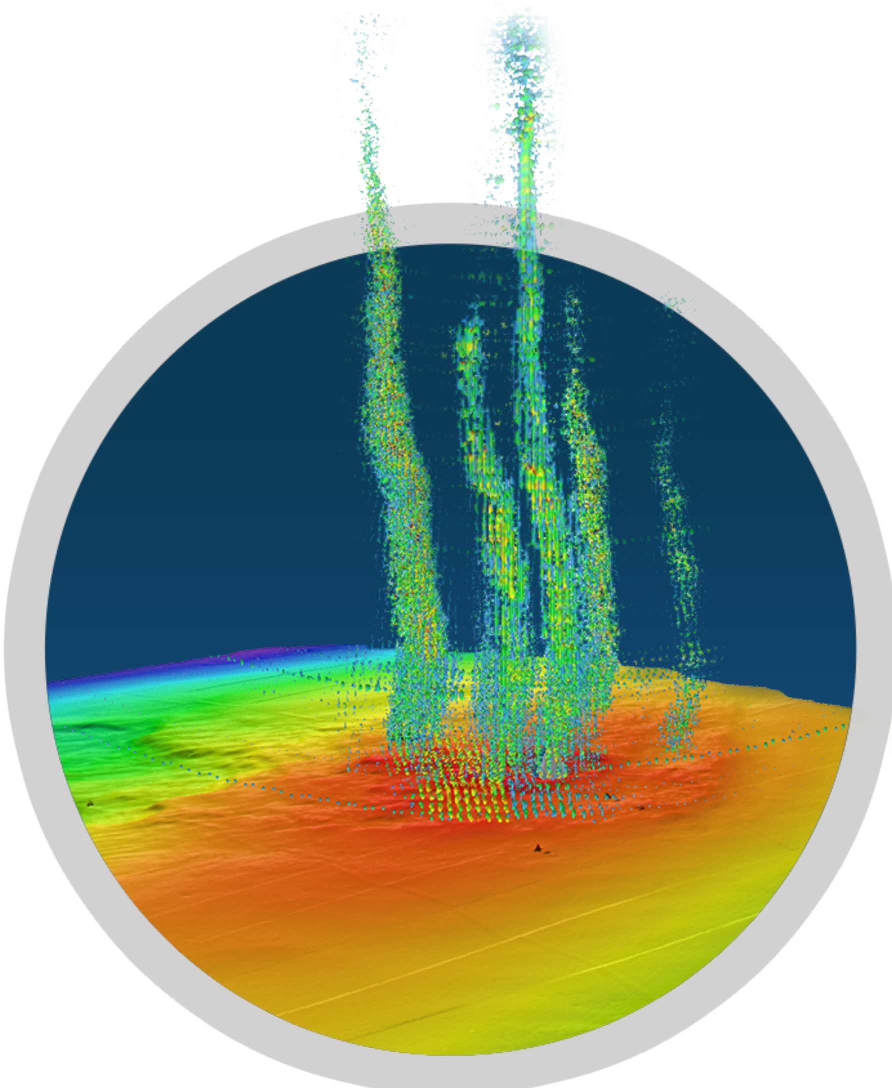

Gas Hydrates and Coastal Applications

Problem, Scope, and Impact

It is thought that ~500–5000 gigatons of carbon are stored in methane hydrate deposits within continental margin sediments (e.g., *Archer et al*., 2009; *Boswell and Collett*, 2011; *Piñero et al*., 2013), with even more methane dissolved and as a gas phase in sediment pore spaces (e.g., *Wallmann et al*., 2012). A significant but unknown amount of methane escapes the seafloor along continental margins throughout the global ocean. Venting of these methane-rich bubbles and chemically altered fluids and their rise through the water column have the potential to impact ocean chemistry and possibly the atmosphere. Methane seeps and hydrate systems have been recognized as a potential geohazard and global climate issue (e.g., *Hautala et al*., 2014; *Johnson et al*., 2015).

The Cascadia margin is of interest because the methane is stored within the accretionary wedge of a major subduction zone. It represents a geologic end member that has a strong tectonic overprint, in contrast to the thickly sedimented passive margins present in the U.S. Atlantic and Gulf of Mexico. On the Cascadia margin, buoyancy forces and stresses induced by subduction allow methane from hydrate layers and leakage from biogenic and deep thermogenic sources to migrate toward the seafloor. However, the distribution of seep-derived methane in the water column is not yet well documented along the Cascadia margin and the impacts on benthic ecosystems are not well understood.

One of the best studied gas hydrate sites along the Cascadia margin is Hydrate Ridge, a morphological high within the accretionary complex between 600 and 800 m water depth that is characterized by shallow gas hydrate deposits and shows active release of methane gas (*Tréhu et al*., 1999; *Torres et al*., 2002). Hydrate Ridge, which has provided new insights into natural hydrate and seep systems, was the focus of Ocean Drilling Project (ODP) Leg 204 (*Kulm et al*., 1973; *Bohrmann et al*., 2002; *Tréhu et al*., 2006) and is currently a key component of the OOI-CA.

The Cabled Array infrastructure is focused around highly dynamic seafloor seeps at Southern Hydrate Ridge (SHR), where the release of large quantities of methane gas and associated dynamic morphology has been well documented. This instrumentation currently provides much-needed insight into actively venting methane hydrate systems on the high-resolution, long-duration timescales required to address outstanding questions regarding sub-seafloor distribution and transport of gas. The main science objectives at SHR now are: (a) defining the temporal evolution of methane hydrate systems in response to seismic events, (b) determining chemical fluxes from the seafloor and the partitioning between dissolved flux and ebullition, and (c) understanding biogeochemical coupling associated with gas–hydrate formation and dissolution.

While the cabled instrumentation provides a valuable stationary data set, it does not offer the mobility necessary to conduct studies related to the high spatial variability of seep systems. Scientific studies that are not currently supported by the SHR infrastructure and could only be conducted using a mobile system include the study of ecosystem dynamics (e.g., disturbance ecology, bacterial mat variability, and trophic links) and the quantification of the impact that seep-derived carbon has on benthic communities and water column chemistry. The deployment of a R-AUV at Hydrate Ridge would fill in spatial gaps, allow for the deployment of mobile chemical samplers, and provide a compelling dataset to complement the existing OOI-CA infrastructure at SHR.

Table 2 shows a compilation of questions and problems that could only be addressed at seep systems through the deployment of one or more persistent, mobile systems. It outlines many of the outstanding topics relevant for gas hydrate and seep systems, including ecosystem dynamics, coastal circulation, carbon cycling, and seep dynamics. The applications also cover survey and maintenance for the cable infrastructure as well as an outreach component.

Table 2. Science questions for seep systems addressed by R-AUV missions

Topic	Subtopics	Required Observations	Experiment Design
Ecosystem Dynamics	Disturbances (trawling, observatories, ROVs, AUVs, infrastructure)	Visual, chemical sensors, multibeam sonar	Time series, settling events and succession, intentional disturbances, areas prone to disturbances
			Habitat, fisheries
	Seeps and fish/invertebrate habitats Trophic links	Visual (stereo photo/video, 360, infrared), imaging sonars, methane sensors, sub-bottom profiler, backscatter, eDNA	Monitor abundances Plan complementary physical samples Small scale behavior, use of variabile habitat in presence of predators
	Bacterial mat variability	Visual, methane sensors, core samples	Photomosaic to inform core/physical sampling cruise
	Zooplankton communities in water column Fish, jellies, siphonphores	Methane sensors, zooplankton quantification, eDNA, plankton pump, plankton video recorder, high-frequency acoustics, forward looking camera	Stationary high-frequency acoustic sensor paired with AUV eDNA
	Pelagic fish stocks and distribution	eDNA, EK80 acoustics, forward camera	Time series, fisheries management, monitoring species of interest at seasonal coastal sites (banks), insight into migrations, size over time, young vs. adult arrival
Coastal Circulation	Upwelling/ocean acidification	O_2, pH, pCO_2, nutrients, ADCP, chlorophyll	Quantify spatial variation of nutrients being upwelled along the margin
	Interactions with canyons/ridges	ADCP, visual and multibeam sonar	Repeat mapping around ridges and canyons

Coastal Hazards	Tsunami monitoring/predictive capabilities/rapid response	Bottom pressure, visual, sub-bottom profiler, multibeam sonar	AUV visits benchmarks for pressure recording; repeat mapping
	Sub-seafloor fluid/stress distribution (earthquakes)	Sub-bottom profilers, electromagnetics	Identifying regions that are prone to high stress along the megathrust, repeat mapping
	Thermal structure and heat flow	In-sediment temperature probe	6 cm – 1 m+ temperature probe in grid patterns to quantify heat fluxes near seeps and other sites of interest
Carbon Cycling	Water column fate of methane (oxidation, mixed-layer, residence time) in diffuse plumes and bubble streams	Methane, acoustics, CTD, O_2, CO_2	Grid pattern at multiple levels: Height, distribution, lifetime of bubbles and dissolved methane Couple with benthic flux/current meters, grid pattern at multiple levels
	Fluid sources and impacts on ecosystem variability	CH_4, CTD, O_2, CO_2, physical samples, carbon isotopes, major and minor element composition	Locate sites of vigorous fluid release, sample for in-situ analysis and store for shore-based analyses
	Efficiency of microbial filter, Nutrient fluxes through sediments and water column	CH_4, CTD, O_2, CO_2, porewater profiles Nitrate, iron, fluorescence, transmissometer	Near sites of dense bacterial mats, measure sediment dissolved components within sediments and within water column
Gas Hydrate and Fluid Flow Dynamics	Distribution of hydrates, free gas, carbonates, microbial mats, mega/macrofauna over range of temporal scales	Digital still cameras, sub-bottom profiler, multibeam acoustics, backscatter, side scan sonar	Surveys involve time series mapping as well as event response (landslides, earthquakes)
	Fluid flow/bubble transport pathways	High-resolution sub-bottom profiler, multibeam acoustics	Frequent near-seafloor surveys to image variability in subsurface fluid transport structure
	Micro-bathymetry changes related to subseafloor gas hydrate and free gas deposits	Visual, sonar, near bottom multibeam, very good navigation, side scan	High temporal and spatial resolution surveys required
Infrastructure	Survey before ROV-based infrastructure maintenance	Visual, multibeam sonar and side scan	Grid surveys of instrument distribution and deployment locations prior to arrival of ROV
	Maintenance of seafloor infrastructure	Visual, manipulators, multibeam sonar	Make simple corrections to seafloor instrument placement or alignment
Outreach and Broader Impacts	Inform public and stakeholders on societal impact of R-AUV-based coastal research; receive input on studies relevant to local communities	Video and still imagery, data visualization	Engage through citizen science activities, town halls, local K-12 and community colleges, industry representatives

Concept of Operations

Effective long-term monitoring of highly dynamic seafloor seep systems requires observations at temporal and spatial scales that are unattainable without the use of R-AUVs. For example, rapid changes in bathymetry have been well documented on inter-annual timescales at SHR, but the mechanisms that control the sub-seafloor distribution of free methane gas and the release of gas into the overlying ocean can operate on hourly or daily timescales (e.g., *Greinert*, 2008; *Schneider von Deimling et al*., 2010; *Romer et al*., 2016). Addressing many of the outstanding questions related to gas hydrate and seafloor seep systems requires the use of a highly capable, adaptable R-AUV to make observations across temporal and spatial scales that span several orders of magnitude. While the capabilities of such a system would be dependent on the requirements of individual studies, many of the routine operations and sensor suites would be similar, regardless of deployment location.

Proposed Locations

Southern Hydrate Ridge is one of the best-studied seafloor seep systems (e.g., *Tryon et al*., 1999; *Suess et al*., 2001; *Boetius et al*., 2004; *Torres et al*., 2004; *Tréhu et al*., 2004; *Heeschen et al*., 2005; *Bangs et al*., 2011; *Kaanberg et al*., 2013; *Philip et al*., 2016) and has played an outsized role in improving global understanding of seep dynamics along continental margins. Because of the SHR status as a type-location of studies related to sub-seafloor gas hydrate distribution and benthic community structure, insights made at this site are broadly applicable across disciplines. In addition to broad applicability, the opportunity offered by the existing instrumentation to augment the data collected by a R-AUV would be unprecedented. While an R-AUV would lend a much-needed mobility component to the infrastructure already deployed at SHR, those same instruments are critical to providing context for any study done using a mobile platform. This contextual data includes sub-seafloor seismicity, diffuse fluid flow rates within sediments, bottom pressure recorders, and acoustic Doppler current profilers. Utilizing the full suite of existing instrumentation to supplement R-AUV studies is required to make progress toward answering outstanding questions regarding gas hydrate and seep systems (Table 2).

While the existing OOI-CA infrastructure at SHR would provide much needed contextual information to accompany R-AUV studies, it could serve to supply the power and communications necessary to operate a R-AUV system. Operation of the instrumentation proposed for seep-related studies would require a reliable power source able to recharge an AUV working in high-current coastal bottom water conditions. Additionally, SHR is visited regularly by OOI-CA maintenance cruises, which offer the opportunity to deploy and recover a R-AUV system with minimal additional ship time.

Baseline and Event Response

Many of the proposed studies (Table 2) require similar baseline sampling strategies, although the spatial scales and sampling frequencies differ according to the requirements of individual investigations. Benthic studies that require high-resolution still imagery for species identification would require the R-AUV to survey in a grid pattern 2.5 m above the seafloor on daily to monthly timescales, depending on the species of interest. A similar sampling strategy would be operative for benthic chemical flux studies and investigations of lower water column chemical variability, which may vary on hourly timescales. For studies related to water column distribution of dissolved methane, grid patterns at multiple heights would enable quantification of the diffuse and bubble fluxes of methane into the overlying ocean, answering a key question regarding the local and regional impact of seeps on water column chemistry.

Baseline sampling strategies would be altered by events associated with possible triggers for increased fluid and chemical flux out of a seep system. Possible triggers for a departure from steady-state conditions include: (a) changes to fluid and gas transport pathways that allow for the build-up or release of over-pressured gas reservoirs at depth (*Bangs et al*., 2011); (b) rapid release of shallow deposits of free gas or gas hydrate deposits, which is inferred based on large collapse features at seeps; and (c) earthquakes that may trigger some combination of altered sub-seafloor transport pathways and enhanced release of solutes into the overlying ocean. Because SHR is located within the only seismically active region of the Cascadia subduction zone (defined as M > 4; *Tréhu et al*., 2015), the deployment of a R-AUV system to complement the existing instrumentation at SHR would allow for improved understanding of the short- and long-term impacts of seismicity on seafloor benthic community structure and on water column chemistry.

Required Vehicle Capabilities

Navigation

What navigation accuracy is required? What navigation strategies might be used (e.g., long baseline, ultra-short baseline)? Seeps have variable bathymetry, thus the vehicle needs situational awareness and obstacle avoidance when navigating close to the seafloor. A forward looking multibeam sonar is necessary. Navigational needs differ between near-seafloor operations and water column operations. Lower frequency acoustics with an extended range (i.e., hundreds of meters), is favorable for water column work, but is challenging near the seafloor. Two different types of navigation systems may therefore be required: bottom lock/DVL for near-seafloor work and ultra-short baseline (USBL) for water column work.

Maneuverability

Will the vehicle be swimming forward during all its missions? Will it need to hold a station (hover)? Will it have to avoid obstacles? Seep and hydrate sites have variable morphology including steep slopes so the vehicle must be able to avoid obstacles. The vehicle would mostly be swimming in a forward motion. Exceptions are during potential collection of physical samples and in case of very slow reaction times of sensors. The Hydrate Ridge area is known to have strong currents occurring locally with maximum speeds of 2–3 kt in the water column and 1 kt near the seafloor. Maneuverability may be influenced by these currents and effective navigation will require offsetting the influence of currents on the vehicle's course over ground.

Vehicle Speed

Vehicle speed may vary depending on the mission goal, such as photo mosaics, methane sensor work, seafloor mapping, water column mapping, etc. Typical vehicle speeds through water during sampling would be 0.5–1 kt, although current speeds of 1–3 kt will add constraints to required vehicle speeds (see *Maneuverability*).

Area and/or Volume Coverage

To cover Hydrate Ridge seafloor surveys during baseline and event response missions requires an operational area of ~25 km^2 at 700–800 m depth. Adding the water column surveys, the overlying water column should be covered up to surface waters.

Operational Tempo

Survey type dictates operational tempo. Variations in bubble stream locations and methane flux from the seafloor into the water column should be surveyed at a large temporal frequency range to collect data about tidal changes as well as daily, weekly, and seasonal changes. Morphological and ecosystems surveys (multibeam, photo survey) need to be conducted at least monthly, preferably bi-weekly.

Autonomy

When is human intervention needed to re-task, and when should the R-AUV respond based on its environment? Is there a scale for human intervention? Human intervention is necessary to identify relevant timescales and modify sampling strategies during the development phase. Once it is operational, human assistance will be needed for sample retrieval and maintenance. Sensor/agency-based feedback for sampling would be appreciated.

Payload

Payloads favorable for a R-AUV include sensors, sonars, and cameras that are available now and those that are either in development or planned for the future. Indispensable sensors for hydrate and seep site dive missions are for methane and carbon dioxide concentrations and possibly isotopes. The models currently available are challenged by reaction time and maintenance needs. However, several efforts are being made to improve these sensors within the next few years.

Sensors available now:

- CTD
- pH
- O_2
- Multibeam
- Side scan
- Sub-bottom profilers
- Cameras (stereo)
- ADCP

Sensors in development or not yet compatible with AUVs:

- CH_4 (concentration and isotopes)
- CO_2
- eDNA
- Sediment heat flow probe

- Physical collection/storage
- Nutrients
- Environmental Sample Processor

Sensors of the future:

- Electromagnetic systems
- 2D or 3D multichannel seismics

The more sensors running during a dive mission, the more power will be used. Trade-offs between instruments mounted and mission goals occur. Feasibility of measurement concurrency must be taken into account. The use of two AUVs would solve this issue. One AUV could carry a sensor package focused on the seafloor and the second AUV could carry a sensor package outfitted specifically for water column work. Tool changing systems are needed in case of a one-vehicle only operation. Additionally, the sensor layout design must focus on minimizing damage during AUV collisions with obstacles.

Complementary Assets to Enhance R-AUV Impact

Based on different needs in navigation and sensor packages for seafloor and water column work, a fleet of at least two R-AUVs would substantially improve the ability to observe the entire four-dimensional sphere of influence related to seafloor seepage. One AUV would operate near the seafloor and a second one in the water column. An additional component to water column AUV observations would be the use of drifting instruments to increase the spatial density of plume measurements.

A requirement for early deployments of R-AUVs at seep systems is the ability to alter sampling strategies as the correct temporal and spatial scales for each project are identified. This could be achieved by deploying the vehicle at an observatory (e.g., SHR), where real time human interaction with the vehicle is possible and where sampling strategies can be modified easily. In addition to the communication and power capabilities offered at SHR, the existing seafloor instrumentation would serve as complementary data to any R-AUV study conducted in the vicinity.

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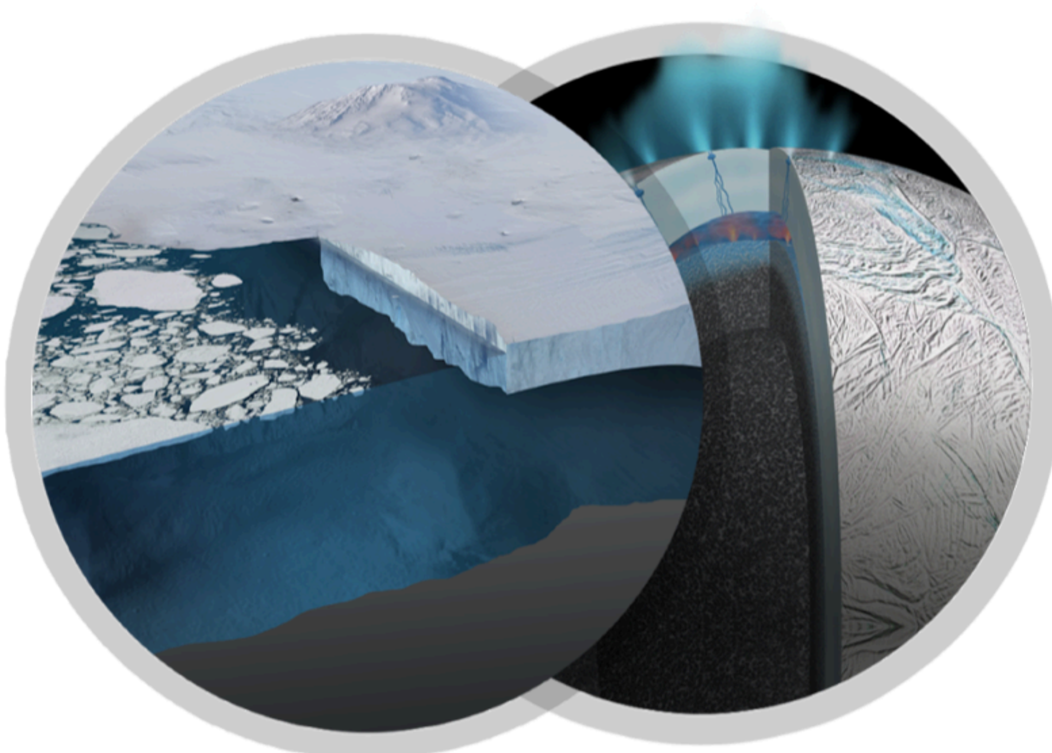

Polar, Under-Ice, and Off-Planet Oceans

Introduction

Polar regions are among the most challenging test environments on Earth. However, science missions in these environments are essential to understanding (geo)physical and (bio)geochemical processes on Earth (*Scambos*, 2017; *Dutrieux*, 2014b). Executing science missions to polar or under-ice environments is challenging due to factors including temperature, physical constraints that come with ice drilling, accessibility of the seafloor and AUV, moving sea ice and ice sheets, and associated complex sub-surface communication with the vehicle.

Knowing that Earth is not the only body in the solar system with an ocean, off-planet missions seek to understand if there are independent origins of life in other worlds (Figure 7; *Hand and German*, 2017). These missions are encumbered by the additional hurdles of limited mission payload, space transport, extreme temperatures, radiation environments, and inaccessibility for direct communication. Earth's polar regions serve as an excellent 'jump-off' point in preparing for off-planet missions by testing space instrumentation and systems in relevant extreme environments. Both families of under-ice missions, on Earth and in space, are motivated by the human drive for exploration, seeking to better understand how life originated and what the extremes are under which it can exist and evolve.

The working group "Polar, Under-Ice, and Off-Planet Oceans" at the workshop identified (geo)physical and (bio)geochemical research to be the two priority areas of exploration for Earth-based missions. The following science questions were considered the most relevant in these categories, especially those that would benefit from R-AUVs.

Biogeochemistry

- How does life thrive in under-ice environments? What are its limitations? (Iron limitation, CO_2 sinks, paleo nutrient flux at glacial grounding line)
- What sustains ecosystems? (seasonal)
- What are the proxy and direct indicators of life and how do they vary?

Geophysics

- What is the physical geometry of ice and its evolution?
- How do we ground truth remote sensing data? (Ground truth both airborne and remote sensing data to extend local to regional; *Gourmelen*, 2017)
- How do polar oceans interact with global oceans? How do polar oceans interact with ice? (in four dimensions)
    - Ice geometry evolution and relationship with ocean heat
    - Boundary layer scale
    - Cavity scale
    - Structure of ocean currents/abyssal water formation
    - Albedo variability

- Global warming and feedbacks associated with sea ice and ice sheet melt
- Under-ice heat flux/transport
- What are the mechanisms that affect melt, and what are their relative contributions?

- How does the atmosphere interact with ice?

Within biogeochemistry, questions revolve around the physical conditions, as well as seasonal changes in life. The geophysics section poses questions about the ice, the atmosphere, and the oceans, and their temporal and spatial interaction. These sets of questions also implicitly ask for the long-term trend, and what effect global warming has on their markers.

Ideally a group of these science questions would be explored during any planned mission. On Earth, an appropriate vehicle would need to have a range of hundreds of kilometers to bridge the distance from a 'safe' docking location to areas of interest and back.

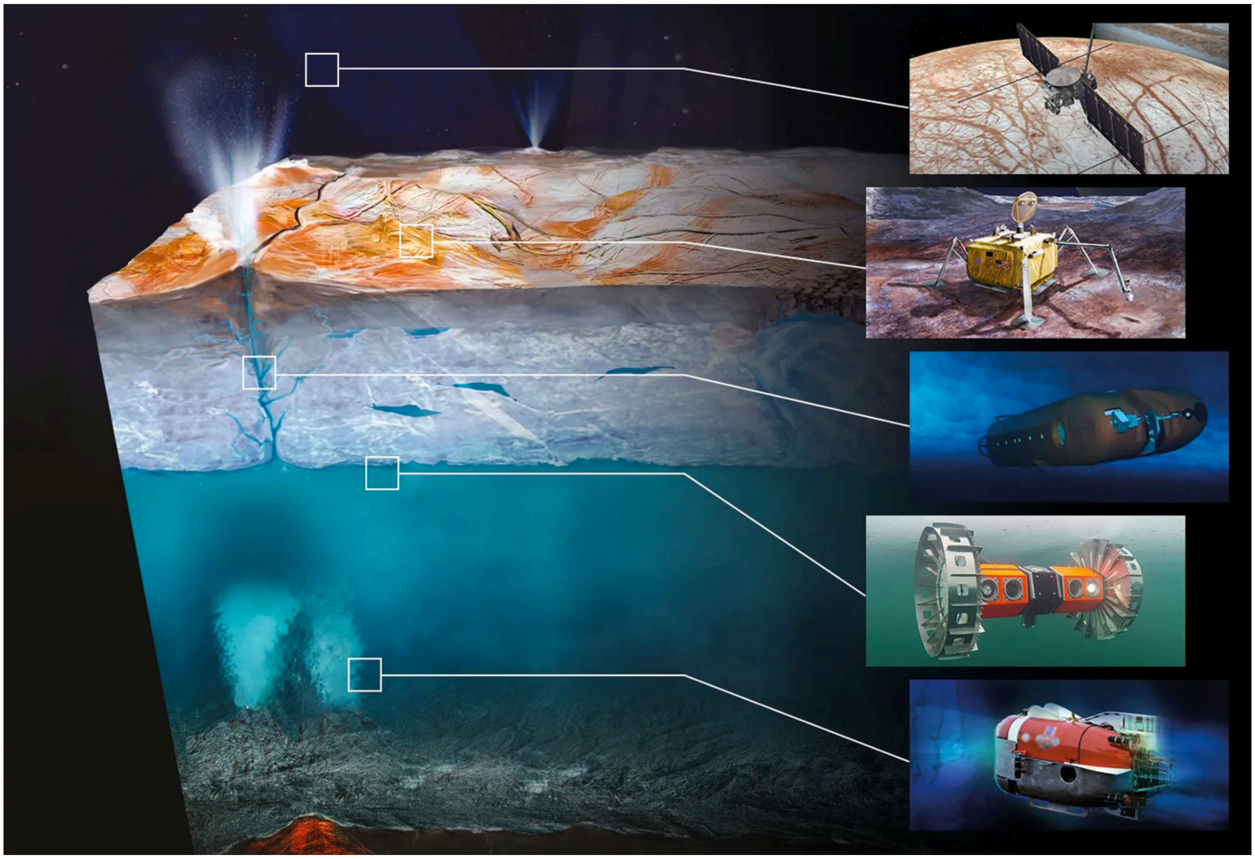

Figure 7. Vision for Ocean Worlds Exploration Program highlighting a R-AUV as a vital tool for investigating seafloor fluid flow systems in the search for life (*Hand and German*, 2017).

Off-planet missions would benefit from the same types of inquiry as Earth-based missions. Additionally, specific off-planet ocean science questions would include:

- Does life exist beyond Earth?
- Can we use physical and biogeochemical sensing on other planets to prospect for seafloor processes as we do on Earth?
- What is the exact composition (total salt content, ratios of major salts) of the salty oceans on other worlds?
- What is the nature of off-world seafloor fluid flow (assuming it exists)?

The working group agreed that there is only a limited amount of information about polar regions, as well as off-planet ice, available at this point — particularly, seasonal long-term observations are very rare. Any observations would provide more data than we currently have in many cases.

The long duration sampling time and availability of an R-AUV makes possible scientific discoveries that were otherwise extremely difficult or unthinkable. Four main areas of impact were identified from having R-AUVs available as a tool for scientific discovery.

- R-AUV presence in polar regions is critical to being able to respond to events like calving, drainage, and polynya openings.
- Long-term observations from R-AUVs will capture data that help us understand the effects and mechanisms of global sea level rise.
- Ground truth data to benefit satellite missions is only possible on a large scale with R-AUVs. These provide the data necessary to understand and model physical phenomena that can then be applied worldwide.
- Off-planet R-AUVs can carry instrumentation that answer the fundamental questions about life in the universe.

Concept of Operations

The functional requirements for a R-AUV to provide the science data outlined by the group were assessed. We imagined a vehicle that has a scheduled mission to collect baseline data 4–6 times each year to sample seasonal variability. The path of this mission can be somewhat pre-planned at first, although the frequently changing and unknown terrain under an ice shelf, for example, makes it difficult to provide exact coordinates and requires some autonomy from the start.

During a mission, the vehicle would need to travel long distances and then autonomously detect and survey a feature. Seasonal time scales were considered and it was determined that a mission every 2 months (every 3 months at minimum) would be necessary to acquire reliable baseline data. Between missions the vehicle could be placed in sleep mode in a safe location such as a docking station. The most useful duration of a sampling mission was suggested to be between 24 h (typical) and up to 2 weeks for projects like tidal assessment.

The vehicle would have two modes — one for baseline sampling, and one for event response. Event response mode would include higher frequency sampling of key parameters of interest, and would be triggered by some specified measurement indicating the start of an event of interest. The vehicle would be able to interrupt the current mission to respond to such an event. We foresee that because events are not likely characterized precisely in advance, not least because so few data are now available, most event response capabilities would still require a human in the loop.

Four areas were identified by our team that need to be taken into account when planning a R-AUV for polar regions: docking, risk management and failure approach, navigation, and communication (Figure 8).

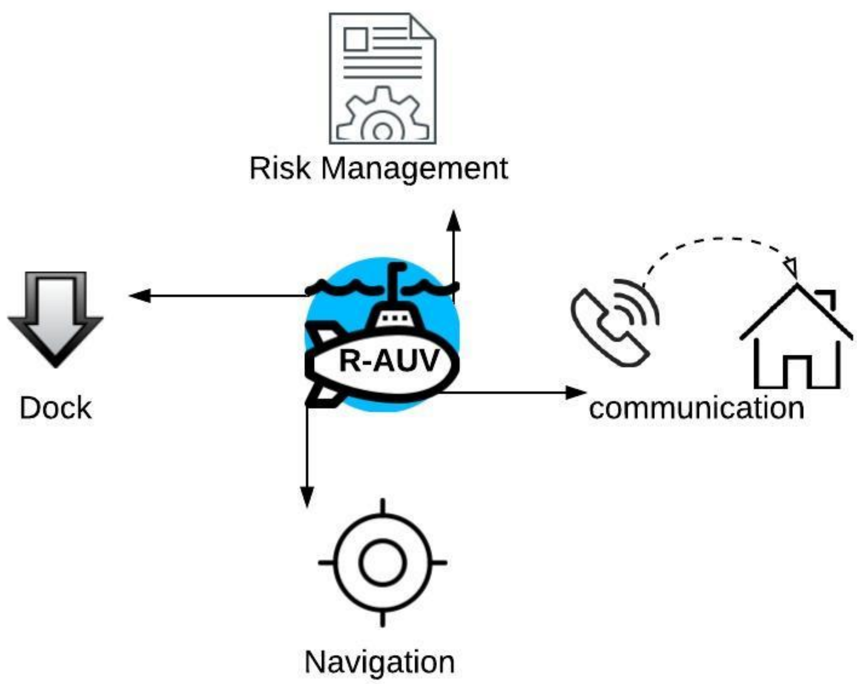

Figure 8. Four areas of interest for planning R-AUV missions in polar regions.

Docking

The question of a dock is of particular interest because there is no clear ‘safe’ spot close to the ice shelf year-round. Having a docking station below the ice was considered safer by the group, but brings its own challenges regarding communication and potential servicing options. A dock could be used for data download and communication with the home base (depending on dock location), and for battery charging. To mitigate safety and accessibility concerns due to moving ice, the group considered possible solutions. Mobile docks, moving vertically and/or horizontally, would allow the dock to be under water/ice for most of the year, and make contact with air to allow communication of data once a year. A similar idea was to have an AUV as the 'dock'. This would mean multiple smaller vehicles are delivered and serviced by a larger vehicle, allowing a lot of flexibility and adaptability for various scenarios, but potentially requiring higher degrees of automation.

Navigation

Currently, navigation is performed by humans monitoring progress, and not at the level of autonomy without human interaction. One of the main questions highlighted by the team with respect to navigation was finding a navigational reference and providing ground truth measurements for the R-AUV. Once under the ice shelf, the vehicle is out of reach for communication, and topographic data is not available and/or highly inaccurate in almost all cases. The working group considered the idea of dropping 'breadcrumbs' — a trail of navigation beacons that would allow waypoint navigation and enable the vehicle to find its way back out from under the ice over a long distance. This might also allow node-to-node communication with the vehicle.

Another concern was how the vehicle could determine if there was an error in navigation, because no redundant information is readily available. Navigation using large-scale gradients like the magnetic field, the ice topography above (which is well mapped at > 1-km scales), or even water density structures were considered in this context.

Communication

Communication with the resident vehicle enables a human in-the-loop for certain decisions, as well as data remittance. Our team considered data transmission as secondary, providing the data were stored safely; receiving data once or twice per year was considered sufficient.

To store science data safely, the dock as a relay, if available, was considered a lesser risk than storage on the vehicle itself. Achieving data redundancy was considered desirable.

However, the lack of communication was still considered one of the greatest technology gaps to enable long-term polar missions due to the lack of intelligent AUVs. A human in-the-loop was still considered an important part of the exploration. A solution to this that would potentially allow low-level communications is the vehicle leaving 'breadcrumbs' in its path in the form of nodes capable of serving as beacons for navigation, as well as able to relay information from node to node back to the dock from under the ice.

If or when a vehicle is developed with a high degree of automation and intelligent decision making, and the data obtained are stored reliably, minimal communication to the vehicle was considered acceptable.

Risk Management

The under-ice environment is unknown and to a large extent unmapped. Having thick ice at the surface also implies that usual fail-safe strategies to release weights and gain buoyancy to reach the surface and wait for help is inoperable. This means any mission into these areas is at greater risk. This is compounded by the lack of communication with the vehicle.

The working group discussed risk mitigation philosophies and strategies on this premise. A mission was considered successful if science data were gathered and returned — in the extreme case even at the loss of the vehicle. Apart from redundancy and systematic long-term testing of the vehicle, the concept of 'graceful failure' was considered extremely important for the success of the mission. This means that even if some parts of the vehicle fail, the vehicle should ideally be able to be recovered, or at the very least be able to relay the data gathered in some way.

Self-identification was also considered important. The vehicle would then be able to self-assess, and send data as to what has gone wrong, and ideally decide how the mission can continue.

Proposed Locations

- Ice shelves in the Ross Sea: these are the focus of abyssal water formation for the global oceans, and therefore of high relevance to the global thermohaline circulation and the climate system

- Amundsen Sea shelves: these are the focus of intense melting by temporally varying oceanic heat content, having a large and mostly unpredictable contribution to global sea level rise

- Greenland shelves: many of the processes and impacts in the Amundsen Sea are similar there, with the additional complication of significant atmospheric driven seasonal melt

- Chukchi Sea: shallow with seasonal ice formation, relevant to current events; fisheries, oil exploration, etc. activities; a good candidate for cabled observatory

Baseline and Event Response

Baseline

- Temporal and spatial range:
    - 3–4-month intervals
    - Year-round coverage
    - 4-D sampling at 50–100 m
    - Benefit of spatial variability during winter: the ability to sample the upper water column; moorings are constrained to a single location and limited to the lower reaches of the water column to avoid drifting icebergs

- Biological observations:
    - Seasonal temporal scale to capture seasonal variability
    - Geochemistry: trace metals
    - Light/PAR
    - eDNA
    - Acoustic environment

    - Multi-spectral camera

- Environmental observations:
    - Temperature, salinity
    - Currents, turbulence
    - Turbidity (backscatter)
    - Ice geometry/roughness
    - Geochemistry: O_2, carbon, trace metals, noble gas, sediment
    - Ice structure (coring/imaging)

Event response:

- Temporal range: 1–2-day events and days to weeks to capture before, during, and after
- Appropriate sensor suites on R-AUV ‘awakened’ to measure:
    - Phytoplankton blooms
    - Under-ice lake drainages
    - Freshwater signal
    - Polynya opening

Operational capabilities/requirements for baseline data collection and event response:

- Perform vertical sawtooth survey patterns
- Act as a data collector/data mule
- Trigger/manipulate/retrieve/communicate with dormant, distributed, low-cost sensors and moorings
- Respond to satellite data

Typical Mission Profile

- 100-km range per mission
- 0–2000-m depth, mostly ice covered, grounding line at 2000 m
- Transit from safe station to under cavity, profiling water column and geometry of ice and seabed, reaching grounding line
- 4–6 missions/year

This mission profile (Figure 9) was considered typical, and could meet requirements for most biogeochemical and geophysics science questions. The system that could meet these mission requirements and steps toward achieving this vision were discussed by the team.

Vehicle Development Strategy

The vehicle’s instrumentation is highly dependent on mission scenario. A modular vehicle that could accommodate a range of instrumentation settings was discussed. The mission vehicle was compared to cube-sat principle, where setting certain parameters of the vehicle allows integration of a range of instruments and software for testing and science missions. In this context, a competition for vehicle design or certain components within the community was suggested to catalyze development and involvement. Sputnik was another comparison drawn, because that mission was to prove it was possible; the focus was not on the scientific outcome.

Another development strategy proposed was to deploy many smaller instrument packages to reduce the risk. This could be in the form of several R-AUVs that return to one docking station. 'High-risk, low-cost' missions were also discussed, where relatively simple and small R-AUV platforms are developed. Taken to an extreme, we found that implementing just instrumentation on swarms of small platforms (e.g., gliders and floats) might temporarily serve the purpose of gathering data.

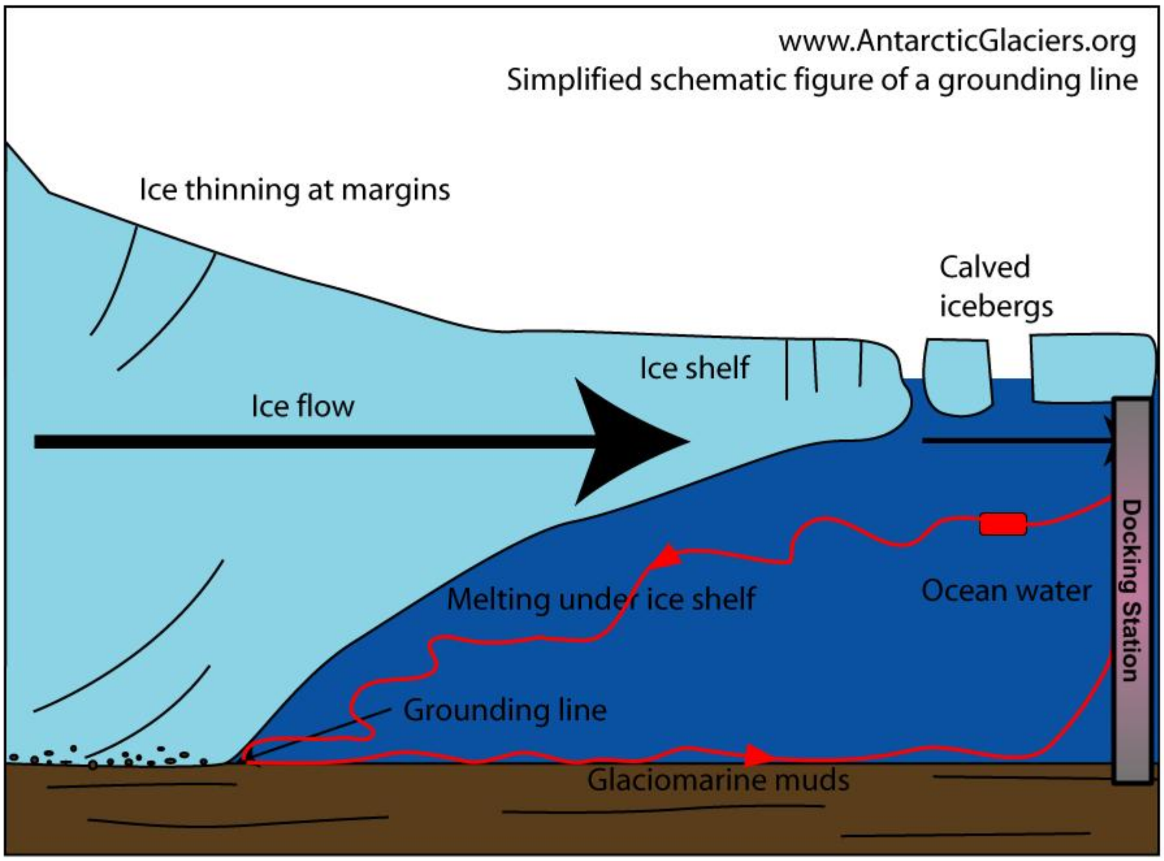

Figure 9. Sketch of a typical mission profile with docking station.

When defining the main characteristics for a R-AUV — resident, autonomous, and vehicle — to mean being able to gather data for periods greater than 3 months while being able to navigate the terrain on certain routes, a step towards R-AUVs in polar regions has already been made (*Dutrieux*, 2018) by deploying floats and gliders near and under the Dotson Ice Shelf in West Antarctica. Assets were deployed there for over 1 year. The authors of this study note that there is a need for complementary, very precise horizontal position sensing capabilities missing in these platforms using traditional acoustical methods, whose accuracy is on the order of 1–2 km.

In building a financial and technical framework for a system, requirements and boundaries for energy, docking, reliability, and communication were considered. The team agreed that working on the lowest hanging fruit to set a precedent for R-AUVs was the fundable path for development.

Funding

Funding mechanisms discussed for developing a high-risk vehicle platform were the National Oceanographic Partnership Program or a suitable philanthropic organization.

Energy

Because setting up a year-round accessible wind or solar powered charging station is difficult in polar regions, a battery powered mission was considered. The maximum payload a crane could deploy as a bounding scenario is 10 t. Implementing 10 t of alkaline batteries and housing would result in 500 kWh as an upper bound of energy for a mission that does not have a charging provision. The cost of this package is estimated at ~$40k.

Reliability

Long-term reliability of the vehicle and thus true residency was identified as one of the main technology gaps within the group. This encompasses several areas of work, including energy management to extend time available per battery charge, docking or anchor station for recharging and data redundancy, onboard risk/failure management, and autonomy and self-identification of failure modes.

Currently, the resources used for ship time to access the site (~$6 M) are greater than the resources for an autonomous vehicle (~$3 M). The vehicle can thus be considered a hardware asset that may not have to be retrieved if it fails, depending on the circumstances. The core product of a science mission is data. We thus agreed that instead of making the reliability of the vehicle our first priority, we should ensure data retrieval. Failure modes and responses need to be assessed with this in mind to ensure that data can be recovered. Under-ice communication and redundancy of data storage are considered important factors toward this goal.

Scenarios to increase survivability and reliability were discussed, and the following questions were posed for further investigation.

- Could reliability be increased by increasing the number of vehicles? What does this mean for the docking station? What does this mean for the functionality of one vehicle (maybe not every vehicle needs to be able to do everything)?
- Is full autonomy required in a first test plan? Can we instead have a planned mission that allows us to gather under-ice data long term?
- Should there be watchdogs and humans in-the-loop to reduce the likelihood of overlooked errors, e.g., if mapping data are not of sufficient quality decide to not leave the docking station?

- Because docking itself can pose a risk (depending on the location), can we anchor? How would we ensure power for the mission in this case? Current batteries can traverse up to 200 km on one charge.

- Communication with the vehicle matters for reliability, especially under ice. Could we implement a multi-hop to open water/mooring network, or communicate through ice?

During group discussions three vehicle concepts emerged.

- Ultra-long duration vehicle with sufficient batteries to not require docking. If a vehicle makes a transect, anchors (e.g., near grounding line), and then makes a return transect one month later, battery capacity is doubled.

- Docking station, with several, lower cost, smaller payload, ‘disposable’ vehicles.

- A hybrid between the two, e.g., where a station provides data exfiltration only (via blue communications or a physical hard drive release).

Next Steps

A few AUVs have (or are close to having) the capability to do such missions, with various payloads suiting the scientific needs. The main issues at hand are residency and docking. The community would need to work on extending the operating time of the vehicle, e.g., optimize the vehicle’s ability to sleep and wake up. Developing a docking station system for recharging and data redundancy, and overall improved energy management are also paramount concerns.

Other high-priority items include:

- Developing a ‘watchdog’ or self-awareness system for the vehicle
- Developing an under-ice communication system — to and from ice or seabed station
- Risk management and mitigation: the vehicle operating under ice requires adaptable procedures to respond to events and enact mitigation practices
- Reliability and survivability of vehicle sensors and safety of stored data

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Maintenance and Operation of Installations

In contrast with the other workshop sessions, the maintenance and operations session was balanced between potential end users and providers entering or considering entering the resident vehicle market. Notably, the participants most strongly involved in R-AUV development represented commercial interests; there was minimal representation from active academic researchers into AUV residency, although there were representatives from research operators of AUVs (e.g., Woods Hole Oceanographic Institution Deep Submergence Laboratory). Given the abundance of commercial operators, active discussion into the potential of R-AUV systems was somewhat muted, as participants may have viewed each other as potential competitors. However, there was considerable agreement on the challenges of developing R-AUV systems, especially compared to the development arc that led to the commercial availability of AUVs in the early 2000s. Of particular interest was the role of supported research and development to bootstrap challenging, but essential, technologies required for true vehicular residency on the road to full commercialization.

While participants were not effusive on their business prospects, a great deal can be gleaned by observing the (public) activities of R-AUV developers, many of whom were in attendance. At the time of the workshop, there had been several public announcements of commercial R-AUVs, primarily targeted at the energy industries.

Energy Industries

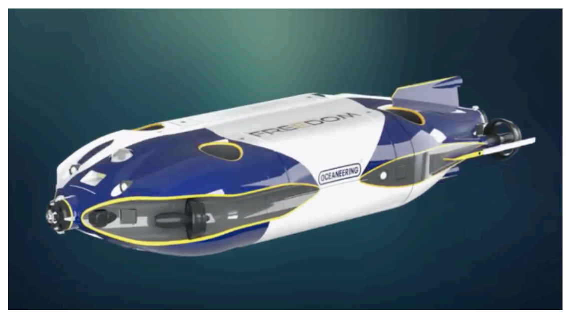
Any consideration of the role of R-AUV systems for industrial users must acknowledge the intimate, yet often not completely aligned requirements of industrial users — historically the extractive industries, though increasingly also aquaculture and renewable energy — and scientific users. Much of the current state-of-the-art of subsea engineering has been developed using oil and gas funding in response to their specific needs, and thus, to a certain degree, those industrial needs define what technologies are readily available and what is considered achievable in the ocean. This understanding must be tempered by the strict reality that industrial users are driven strongly, if not exclusively, by the underlying economics. Not only must new technologies be profitable, or increase profitability, but they must be profitable within the current state of the energy markets.

With that said, the commercial sector is keenly aware of the structural limitations built into their current use of subsea robotic systems. Particularly, the emergence of AUV technology has led to close examination of the factors that drive the costs of surveys. The costs of hull-mounted or towbody sonar surveys are driven by ship operating costs, including transit to/from the site as well as execution of the survey. For accurate localization of the towbody, particularly for deeper surveys, a second tracking ship may be required. The cost of the survey is thus driven largely by the cost of keeping the ship(s) on station.

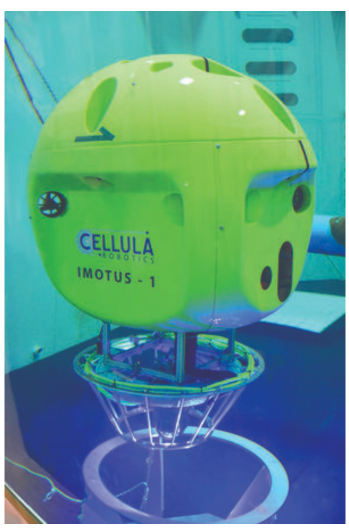
The current generation of AUVs are used primarily to perform wide area surveys, in direct replacement of sonars deployed on towbodys. In the current mode of AUV operation, an AUV tender, often a repurposed survey vessel, transits to the survey area with the vehicle, then launches the AUV. Given the current maturity of AUV technology, the tender ship then follows the AUV on survey, performing the role of the tracking ship, improving the localization of the resulting survey as well as ensuring the integrity of the AUV and maximizing the chances of vehicle recovery should it surface unexpectedly.

Despite the advantages offered by 'cutting the cable' to the AUV, the continued reliance on the ship means that AUV technology is, at best, moderately competitive with conventional towed surveys given the capital costs, staffing requirements, and risk of loss of the support ship. In part this reflects the state of AUV maturity as well as the understanding of the relative risks to the AUV as a capital asset if run truly autonomously. While the expected technical trend is for AUVs to become more reliable, to feature more accurate navigation, and to be capable of more autonomous operation, leading to scenarios where a ship does not need to be dedicated to an AUV while it is on a mission, some support vessel will remain necessary for launch and recovery.

Saab Sabertooth (Image: SAAB, Inc.)



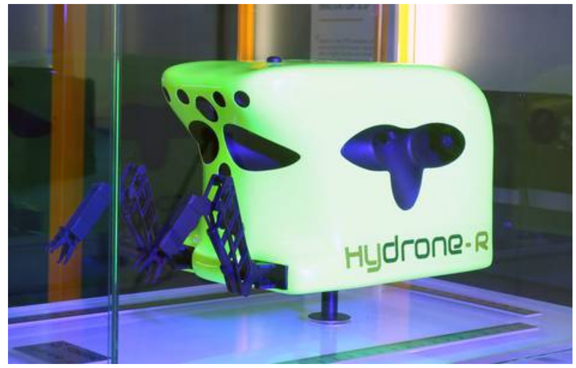
Oceaneering Flatfish (Image: Oceaneering, Inc.)



Cellula Robotics IMOTUS-1
(Image: Cellula Robotics)

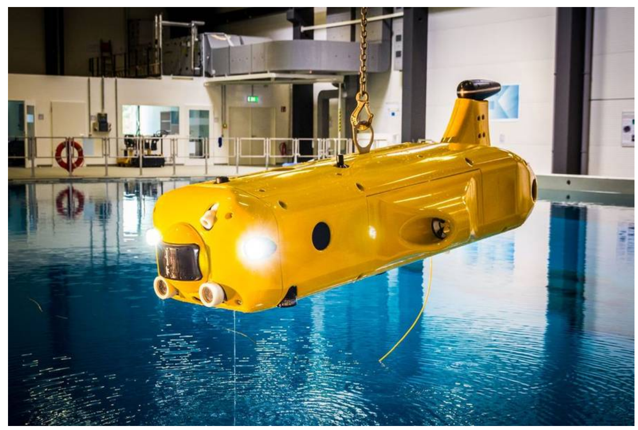
Houston Mechatronics Aquanaut
(Image: Houston Mechatronics)

Subsea 7 Autonomous Inspection Vehicle
(Image: Subsea 7)



Saipem Hydrone
(Image: Saipem)

DFKI Flatfish (Image: Florian Cordes, Ground Truth Robotics, Gmbh)



The lesson that follows is to look for scenarios where the ship can be removed from the operation altogether, either through development of AUV technologies that can transit long distances from a central staging point to a survey location, or through use of resident vehicles. The latter would not necessarily require a revolutionary leap in vehicle design (e.g., energy density), although it would only support the limited cases where survey tasks are performed repeatedly in well-defined physical locations, e.g., the areal or linear survey of pipelines, cabling, and other existing infrastructure on the seafloor.

Having explored the possibility of removing the ship from AUV operations, as similar logic can be followed for the inspection and intervention tasks currently performed by ROVs. Again, the costs of ROV operation are driven by the operational costs of the support ship, which must be suitably large for intervention-class ROVs. The costs of operating the support ship are ongoing, not only when the ROV is active on station and working, but between operations, during transit, and extent while idle.

Unlike the path from towbody to survey AUVs, the evolution of ROVs into resident vehicles is less clearly defined. The most straightforward and achievable version of residency could take a conventional ROV and simply tether it to fixed infrastructure rather than to a ship. This entails significant engineering effort to install an appropriate ‘garage’, tether management, and power and data on the infrastructure, but this approach neatly circumvents many of the significant challenges in vehicular autonomy that come with removing the tether. Whether semi-autonomous, or fully tele-operated, the tether provides high bandwidth monitoring and control of the vehicle over the network, and allows a human operator to intervene for challenging operations, including manipulation and launch/recovery.

The leap to an untethered ROV-like vehicle requires addressing the autonomous execution of the tasks that differentiate a ROV from an AUV: close, high-degree of freedom operation in proximity to objects in the ocean, inspection, and manipulation. Compared to the relatively straightforward open-ocean navigation required by torpedo-shaped vehicles, achieving this level of autonomy is a significant challenge.

Despite the technical challenges, thus far, industrial interest in vehicular residency has sought to cover both use cases with a slight bias toward the AUV-like survey tasks, if only due to the greater existing understanding of autonomous operation of that class of vehicles.

The oil and gas vision for residency is remarkably consistent across manufacturers. Vehicles will be pre-staged on docks attached to seafloor infrastructure, taking advantage of existing power and data connections. Vehicle tasks split nearly into AUV-like and ROV-like modes, with the AUV-like visual, acoustic, and nondestructive testing survey of linear seafloor infrastructure being largely autonomous (Figure 10).

Vendors also typically describe an ROV-like mode for inspection and manipulation (Figure 11). This mode requires far more sophisticated, world-relative situational awareness and autonomy, and manufacturers understandably do not promise fully autonomous behavior in the near future. Instead, close inspection and manipulation tasks would be performed with the help of a supplemental, data-only tether (tying the vehicle back to existing infrastructure), or via a short-range, high-bandwidth, free-space communication channel, e.g., a laser-based optical modem.

Defense

Residency is likely to impact military usage of autonomous vehicles in two ways: the first echoes the industrial motivation for R-AUVs, that is, the ability to have underwater vehicles present on station, potentially for long periods of time to perform repeated or reactive missions. The second is the capacity of R-AUVs to operate subsea without a permanent surface expression (e.g., a support ship), offering a tool for maintaining a low-observability presence in the ocean.

To date, military experimentation with R-AUVs has focused primarily on torpedo-shaped or survey vehicles, e.g., the U.S. Office of Naval Research Forward Deployed Energy and Communications Outposts (FDECO) program sought to establish a baseline technology for subsea power and data exchange with AUVs, envisioning networks of docks supporting fleets of vehicles.

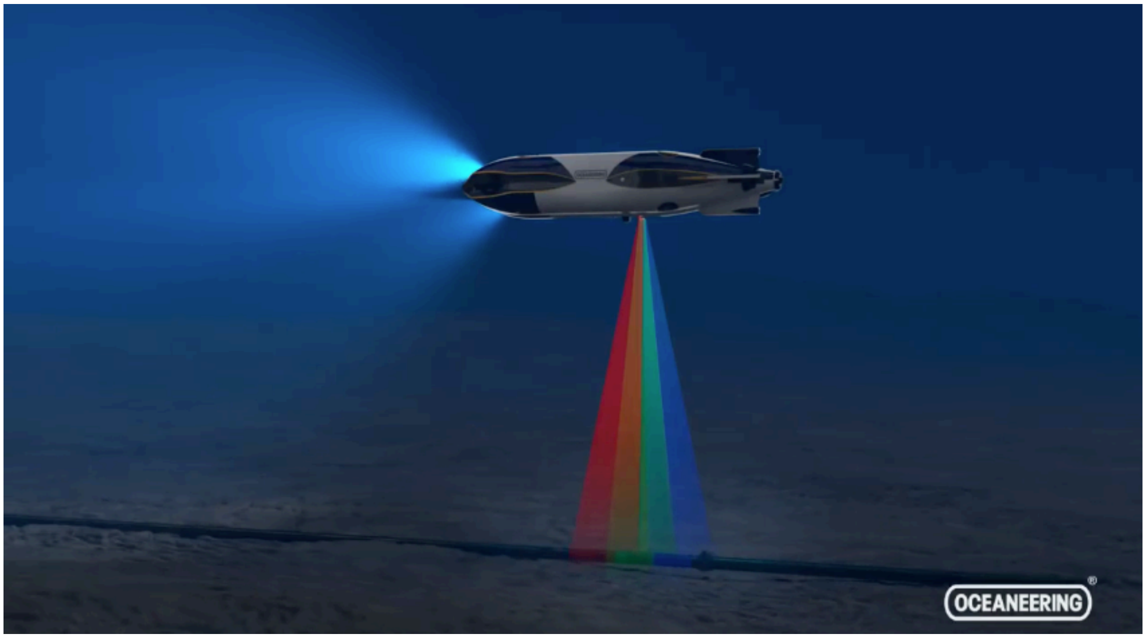


Figure 10. Conceptual art of Oceaneering Freedom vehicle performing autonomous inspection of a seafloor pipeline. (Image: Oceaneering)

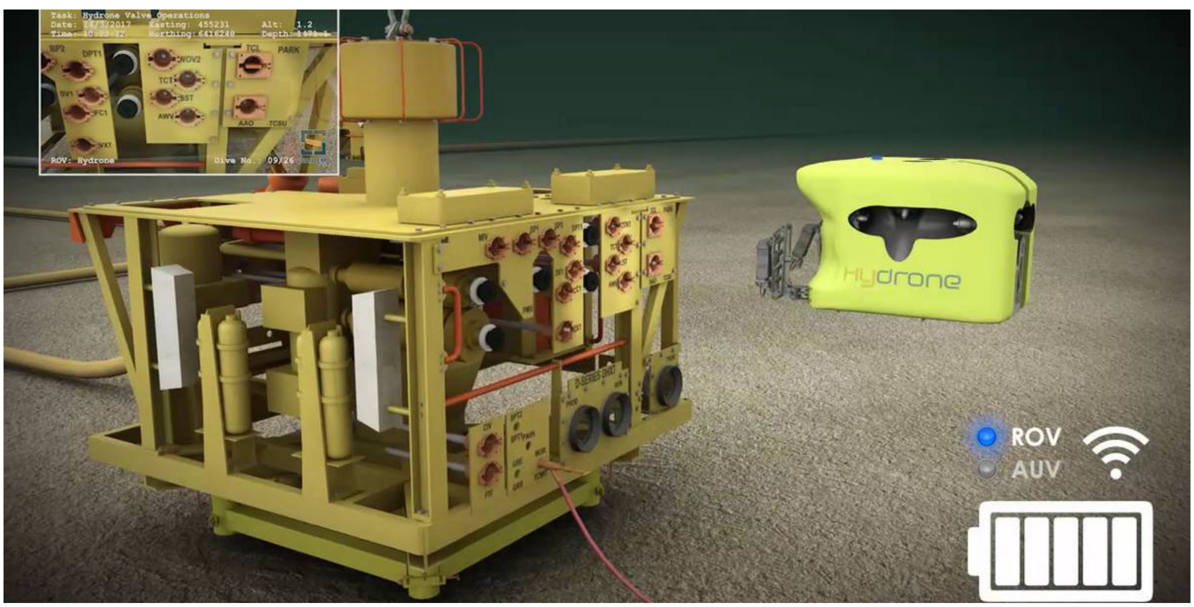


Figure 11. Conceptual rendering of Saipem Hydrone performing an autonomous, untethered intervention on a seafloor wellhead. (Image: Saipem)

Alternative Markets

Beyond the established offshore intervention industry, there is keen interest in R-AUVs to automate markets that might not be served by the current state of ROV and AUV technology. A prime example is the inspection of marine hydrokinetic (MHK) energy generators. These generators are, by definition, located in sites of high marine kinetic energy — high currents or tidal motion, high seas, or both. Access from the surface, particularly during periods of peak operation, could be treacherous for the ROV and support ship. Once on site, a conventional human-controlled ROV would be at high risk for collision with the MHK generator itself. Conversely, an R-AUV could use its internal autonomy and situational awareness (required for navigation and docking) to maneuver in proximity to the MHK generators.

Similarly, the core concepts of residency could be beneficial for industries that have not traditionally used ROV or AUV technology. For example, as aquaculture becomes an increasingly important industry, resident vehicles may become an invaluable tool for the continuous sub-surface monitoring and patrol of fish pens. Such vehicles might look radically different from the ROV-derived oil and gas vehicles but will similarly rely on residency to achieve their mission goals.

Participants also discussed several applications that require long-term or repeated observation of underwater sites, e.g., repeated monitoring of dynamic, environmentally sensitive data (e.g., tracking industrial or waste water outflows), providing port or coastal security, and inspection of civil infrastructure in cases where high-frequency inspection is required, or where it may be impractical to deploy a conventional ROV. R-AUVs could also be used to automatically search for and track animals in relatively constrained areas, e.g., monitoring the presence of orcas in Puget Sound. An unconventional scenario was for the inspection of ship hulls and sea lockers before entering biologically sensitive waters. Under normal operations, this would require either divers or an ROV to intercept the ship and perform the inspection. As an alternative, a R-AUV could be situated in an unstaffed inspection point offshore and controlled remotely, or could operate autonomously.

Challenges

Discussion on the topic area ‘Maintenance and Operation of Installations’ covered the possible domains of R-AUV missions, as well as the unmet operational objectives that require continued research, development, and testing.

The latter question maps directly onto the technical challenges addressed in other workshop sessions: energy density, recharging, docking, and above all else, reliability. As most participants were familiar with the challenges in developing and testing subsea equipment, most recognized the challenges in achieving the long-term hardware and software reliability critical for maintaining the integrity of a persistent system.

The greatest challenge will be finding time, opportunity, and budgets to perform sufficient testing to have assurance of vehicle performance. Given the greater technical complexity of R-AUVs, as well as the greater risks inherent in the unattended, resident mode of operations, most participants believed resident vehicles could be designed and built using current technology, but questioned whether maturation could be achieved without either significant high-risk investment, or a coordinated effort by multiple funding sources.

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Contributing Technologies

Underwater vehicle residency requires more than a robust and capable vehicle. Several auxiliary components will be part of a system of solutions for long-term remote R-AUV operations. During the workshop, participants considered six technology areas that will each have a critical and synergistic role in driving the success of R-AUV installations:

- Docking systems
- Power sources
- Sensor systems and payloads
- Communications
- Navigation
- Human–robotic interaction and autonomy

While vehicles and subsystem technologies were discussed in relation to application breakouts, a technology-focused brainstorming activity — the speed round — was conducted. Here, participants formed groups and visited each of six stations representing one of the technology areas. At each station, a facilitator worked with the groups to brainstorm about the current state-of-the art, future, and suggested next steps for each technology area (Appendix C). Key takeaway messages are summarized in the following sections by technology area.

Docking Systems

Autonomous underwater vehicle docking has been demonstrated on multiple occasions, but it has not yet become routine in field operations. Low reliability, the potential for biofouling, and a lack of ready power sources have all had a role in minimizing opportunities for long-term residency.

Typical vehicle docks consist of acoustic transponders that serve as homing devices mounted to fixed docking platforms. Vehicles use acoustic signals to align their approach to large funnel-like receptacles on the docking station. In some cases, LEDs or visual patterns have been used to help vehicles fine tune their alignment with the dock. In these scenarios, alignment and dock entry is always a task performed by the vehicle.

In addition to providing a physical shelter for vehicles that may be useful for deployment and recovery, docking stations may be used to recharge and upload data from the vehicle. Both direct plug-in (mechanical connectors) and inductive links have been used successfully for power transfer, and close-range data transfer may be accomplished through physical copper connections (i.e., Ethernet), WiFi, optical, or acoustic modem links.

Some docking efforts have focused on systems incorporated into large, ‘mothership’ vehicles that transport smaller AUVs long distances to their deployment sites. The smaller AUVs are then deployed and must return to the larger transport vehicle at the end of their mission, requiring mobile-to-mobile docking capabilities.

Workshop attendees brainstormed on what future docking technologies might entail. Ideas covered many aspects of docking, from smarter and more active docking components to simplification of dock components, anti-biofouling measures, power sources, and sample storage modules.

The primary function of the docking station is to interface with a vehicle. In several existing docks, this may require precise alignment of mechanical connector components. Because it can be difficult for vehicles to resist currents and perform the fine navigation adjustments needed to align themselves with centimeter or smaller position accuracy, participants discussed methods of simplifying the docking requirements. Concepts were considered such as using line capture, or a less-constrained ‘vicinity’ dock or nest that would make it simpler for a vehicle to get near the dock without having to perform precise alignment. Increasing the distance between the vehicle and dock may then require wireless data and power transfer.

One key aspect of subsea operations in shallow water is the need to minimize the impact of biofouling over time. Therefore, a combination of physical wipers, shutters, and brushes as well as chemical anti-fouling agents, and UV light might be appropriate. Or a small local service ROV tethered to the docking station might be used for biofouling remediation.

Another docking topic considered was the mobility of the dock itself. The ability to install, recover, and redeploy docks using standard ocean-going equipment will enable broad use. The option of self-deployment, such that the dock and vehicle could be dropped from a ship’s deck to the seafloor without ROV support, was explored. In the future, perhaps docks would themselves be able to transit autonomously to their operational location, or be air dropped into place.

Self-diagnostic capability is another important aspect of future docking systems. Smart docks may have the ability to assess their own functions, communications links, and energy supplies, and they would be able to run diagnostics on the connected vehicle(s) to assess the system operability.

Power Sources

Traditional AUV operations are limited by power availability. Vehicles are launched from a vessel and run their mission until the onboard battery is exhausted (typically 10s of hours) at which time the vehicle must be recovered to the ship and recharged. This operational model is vessel and operator intensive and not conducive to long-term deployments. R-AUVs promise to alter this paradigm such that vehicles may perform many remote missions without recovery or vessel support. Vehicles will recharge at in-water docks that are connected to a ready supply of power.

Workshop participants considered alternative approaches to providing power to R-AUVs as well as issues surrounding energy storage and transfer. The following technologies were identified as possible methods by which to power R-AUV operations.

- Shore-based cable (e.g., OOI-CA, ONC)
- Solar
- Wind
- Wave
- Stored power (batteries)

- Diesel fuel
- Fuel cell, including biofuel
- Hydrothermal

Connecting to a shore-based cable may be the most straightforward approach to developing R-AUV capabilities, and comes with the bonus of fiber optic communications. With an ample supply of continuous power and communications, cabled observatories like the OOI-CA, Ocean Networks Canada, and MARS have available instrumentation ports in scientifically interesting parts of the ocean. Cables, however, represent a fixed infrastructure that lack the flexibility to deploy outside of their immediate installation areas.

High-density fuel-based energy systems may lend themselves to long-term deployments, although subsea refueling operations may prove complicated.

The ocean environment itself offers several forms of renewable energy. For example, solar and wind energy harvesting technologies have been used extensively on buoy systems.

Energy harvesting from ocean waves and currents has been demonstrated in recent years, with ocean observing and AUV charging identified as prospective markets for marine hydrokinetics by the Department of Energy (*Powering the Blue Economy*, www.energy.gov/sites/prod/files /2019/03/f61/73355.pdf). For example, the Fred. Olsen BOLT Lifesaver platform generated an average of 3.2 kW over 200 days in 2016–2017. Because renewable sources are intermittent, local energy storage solutions, such as rechargeable battery banks or super capacitors, are used to store energy locally so that it will be ready when a vehicle requires charging.

Energy scavenging from seafloor hot springs (hydrothermal vents) may take advantage of the thermal gradient between single digit seafloor temperatures and the super-heated fluids (up to 400°C) emitted from the seafloor. Alternatively, biofuels derived from marine algae may be converted into energy in situ.

Selecting the most appropriate renewable energy source for any given deployment will likely be site-specific and may combine more than one source, depending on the local current, wave, solar, and wind conditions. Ultimately, renewable energy harvesting systems have the potential to enable long-term, compact installations that may be moved easily from one remote site to another.

Rapid battery charging systems may take several hours to replenish several kWh, partly limited by the battery technology itself. This may mean that 10–50% of a resident vehicle's operational life may be spent in a docking station. To minimize charge time and maximize operational time, alternative approaches such as a complete power module swap (i.e., change the batteries) might be considered.

Investment in efficient energy harvesting, storage, and power transfer in the 0.1–100-kW range will support long-term vehicle residence applications.

Sensor Systems and Payload

R-AUVs will enable oceanographic measurements over unprecedented spatial and temporal scales. Workshop participants considered the measurement types and sensor technologies needed for R-AUV applications. Measurements were identified to support chemical, biological, physical, and geological assessments of the ocean environment.

Chemical

- Dissolved O_2
- Temperature
- Salinity
- Nutrients (NH_4, NO_3, NO_2)
- Methane
- Dissolved gas species (mass spectrometer)
- pH
- CO_2
- Oxidation reduction potential
- Trace metals

Biological

- DNA (Environmental Sample Processor)
- Fish presence (Vemco fish tags)
- Optical imaging (video, stereo camera)
- Particulate, plankton imaging (flow cytometer)
- Acoustic signals (hydrophone)
- Mineral/microbe spectroscopy (VNIR, MIRATR, Raman, LIBS)
- Backscatter/turbidity

Physical/Geological

- Current profiles (ADCP)
- Seafloor bathymetry (multibeam sonar)
- Microstructure

Common challenges among current state-of-the-art sensors include susceptibility to biofouling, the need for frequent calibration, and deficiencies in maintaining accurate onboard time for cross correlation with other sensors. Another challenge posed by integrating multiple sensors in a confined payload module is introducing the possibility of interference.

Conversely, potential future advances in onboard multi-sensor data fusion has the potential to drive autonomous, on-the-fly mission planning to accomplish new and exciting research missions. These might include following the evolution of a volcanic plume into the water column or conducting maintenance on a piece of infrastructure based on inspection results. As sensor development continues, decreased size and lower power sensors capable of long deployments will enable greater vehicle sensing capacity.

Increasingly complex in situ analysis methods are being developed for vehicle operations. During long-term deployments, physical samples will be difficult to handle and store, making onboard analytical systems attractive. AUV-portable versions of mass spectrometers, eDNA samplers, and high-resolution stereoscopic cameras are just some of the systems that have been demonstrated and have the potential, over time, to become smaller, lower power, and capable of longer deployments.

Communications

Resident mobile underwater systems will rely on short-, mid-, and long-range communications technologies to offload data, conduct missions, and retrieve new instructions from remote operators. Terrestrially, radio frequency (RF) transmissions are the preferred method of sending data wirelessly. However, due to the rapid attenuation of RF waves subsea, underwater acoustics have emerged as the dominant mode of transmitting signals to and from operating AUVs.

Typically operating at frequencies in the 10s of kHz, and with ranges of up to several kilometers (with a tradeoff between range and frequency/data rate), subsea acoustic transponders are used routinely for low-bandwidth message transfers, such as sending navigation updates to AUVs or to trigger pre-programmed behaviors. While enhanced spectral allocations have improved acoustic bandwidth, even high-speed commercial modems are typically limited to below 100 kbps, which is several thousand times slower than typical WiFi links. Workshop participants noted that due to bandwidth constraints, efforts to process and communicate only high-level information to and from the vehicle will be increasingly important to autonomous operations.

Other underwater wireless communication technologies have demonstrated utility over shorter ranges. Most promising may be optical communications, with speeds of up to 500 Mbps (Bluecomm) and ranges of up to hundreds of meters (workshop presentation by Norm Farr). Sensitive to ambient light, optical communications are optimally suited to the dark depths of the deep ocean below the photic zone. At very short ranges (10s of cm), underwater WiFi has been used for applications like downloading mission data (*Alford et al*., 2015).

Just as a modern smartphone may connect to multiple complementary wireless devices or networks to perform different functions, which might include a cellular network for calling, WiFi for streaming video, and Bluetooth for local device operation, so too might an AUV system incorporate multiple communications capabilities. For example, an AUV may receive positioning information through acoustic communication, but transfer large data files using a higher bandwidth optical link (*Farr et al*., 2010). Optical links supporting streaming video have been demonstrated to enable operator control of an untethered vehicle for complex or nearfield operations, allowing operators to control vehicles wirelessly, similar to ROVs.[*]

[*] *SAAB Demos AUV/ROV Hybrid, Seaeye Sabertooth, at NASA Laboratory*, 2015. See saab.com/region/usa/sdas/about-saab/media/stories/saab-usa-stories/2015/saab-demos-auvrov-hybrid-seaeye-sabertooth-at-nasa-laboratory/

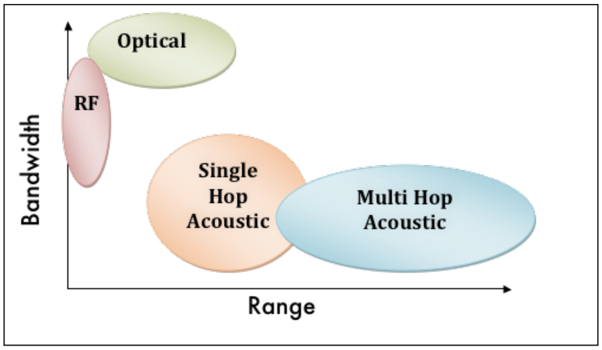

Figure 12. Relative range (distance spanned) vs. bandwidth (amount of data transferred) for subsea wireless options.

To extend communications with R-AUVs over even longer ranges, networking algorithms may be implemented for multi-hop messaging between vehicles and cabled or satellite-connected nodes (Figure 12). For example, a mesh network of acoustic sensors may cover tens to hundreds of square kilometers. One or more acoustic transponders in the network may be connected to a cable or satellite link. With multi-hop routing, an AUV operating within range of any node in the network would be able to receive re-tasking instructions passed from one node to another until it reaches the vehicle. Conversely, the vehicle could pass small amounts of mission information through the network to operators on shore in near-real time.

The long-hop communication, occurring between shore-based operators and the remote resident operating area, is another critical aspect of R-AUV communications. Fiber optic cabled observatories have the potential to provide high-speed communications (speed of light) between remotely deployed resident systems and shore. Remote locations not served by cables might rely on satellite communications, or if nearshore, long-range RF buoys might be feasible.

Navigation

AUV navigation accuracy is necessary to correlate sensor measurements to three-dimensional positional coordinates. Vehicles that operate at or near the sea surface may have frequent access to GPS satellites, but vehicles that remain submerged for long periods must rely on other methods to navigate.

Most AUVs carry onboard sensors that allow for an approximation of the vehicle position, typically using a Kalman filter to estimate position errors. This process is called dead reckoning. Onboard sensors typically used to determine navigation solutions include a compass to determine heading, a DVL to measure speed over ground, and a pressure sensor to track depth. More sophisticated systems may also incorporate a laser ring gyro-based INS. When operating near the seafloor and receiving a good DVL bottom track, vehicle navigation accuracy can be quite good, but even small errors accumulate over time. An error of only 1% of distance traveled will result in missing a target by a full kilometer after 100 km of travel.

When vehicles are diving or operating too far above the seafloor to reference their motion along the bottom, errors accumulate even more quickly, especially in the presence of waves or significant water currents. For example, during a dive from the surface to the seafloor in 3000 m of water, an AUV may accumulate many tens of meters of position error. When AUVs operate accompanied by a vessel, a USBL system with a transducer mounted to the ship is used to locate the AUV acoustically and send corrections based on the vehicle's range and bearing relative to the known shipboard GPS.

In the absence of a surface vessel for long-term resident operations, long-baseline (LBL) navigation may be desirable. A LBL array consists of acoustic transducers mounted at known locations along the seabed. By determining the ranges to transducers in the LBL array, the vehicle triangulates its position.

An alternative, or perhaps addition, to an LBL array is feature-based navigation. This involves identifying distinctive attributes within the operating area and creating a geo-reference for each feature such that the vehicle can correct its position by determining its position relative to the known features around it. In resident applications, AUVs will operate within the same volume of water for extended periods, making repeated passes near certain features. This makes feature-based navigation particularly suited to R-AUV operations. Likewise, simultaneous localization and mapping (SLAM) algorithms may be used to construct a map of a local area and operate within it.

Workshop participants identified navigation challenges for resident AUVs, including the need for repeatable positioning for reacquiring small targets, self-navigating in the middle water column, and even the ability to track animals. Suggestions for improved navigation involve drawing upon a growing set of data from sensing systems onboard the vehicle, which might include water current sensors, gravity and magnetic field variations, or visual systems such as plenoptic cameras. Other suggestions described external systems that might aid AUV navigation, such as a stationary active transmitter with passive receivers on local vehicles, inverted USBL, and using mesh networking to identify and navigate vehicles as they move through the network. Participants also noted that because AUV equipment and operational costs tend to be high, progress will happen more quickly through reducing equipment costs, and creating development platforms with shared access to operational software.

Human–Robotic Interaction and Autonomy

For this discussion, robotic autonomy can be split into the two broad categories of core and mission autonomy. Core autonomy is the capacity for the R-AUV, as a cyber-physical system, to remain functional through a deployment. For safe, long-term operation, R-AUVs require a level of core autonomy well beyond that found in current AUVs, and arguably, beyond that found in most other commercial robotic platforms. At a base level it includes the capacity to reliably perform all of the tasks necessary to ensure the vehicle's safety: navigate to the dock over long distances, avoid obstacles, dock, and ensure data and power transfer. Core autonomy also includes vehicular self-awareness and self-monitoring, again ensuring the vehicle is capable of recognizing circumstances that might prevent it from completing its deployment (e.g., low power) and taking steps to mitigate that failure.

Mission autonomy operates at a higher level and concerns the capacity of a vehicle to automatically complete mission elements without full human in-the-loop control. Within mission autonomy there are multiple scales of task. For example, mission autonomy includes an R-AUV automatically performing a low-level mission task such as use of a manipulator to capture a sample; but it can also include high-level planning about the goals and timing of missions to achieve particular goals. In contrast to core autonomy, some mission-level autonomy, particularly regarding mission planning, does not need to occur on the vehicle itself and may occur on shore or on the dock, which may have more computational power and energy available than the vehicle.

Risks and Risk Mitigation

The discrete technologies needed to field R-AUVs exist. These include maneuverable vehicle systems, wireless charging and data links, acoustic navigation and data networks, and autonomy algorithms. However, the complex system integration and extended periods of autonomous operation needed to achieve a fully resident system carry inherent risks.

Long-term resident operations require AUVs to be deployed for weeks to months, much longer that typical propeller-driven AUVs operate between maintenance cycles. Long-range AUVs, capable of transiting thousands of kilometers, have begun to bridge this gap. Likewise, buoyancy-driven gliders, including Seaglider, Slocum and Spray systems, and wave-driven, solar-assisted surface Wave Gliders have pioneered long-duration autonomous operations at sea. These successes are a solid foundation from which to assess and mitigate the risks of long-term at-sea vehicular operations.

From Prototype to Operations

Often, the phase of technology development between a few initial prototypes and reliable, routine operation is thought of as the 'valley of death'. This can be the most costly part of development, and when the most failures occur. But, it is also where the most dramatic strides forward are made. As with all integrated systems, overall reliability of R-AUVs will be dependent on the cumulative reliabilities of the various system components. As the number of essential components increases, the overall system reliability is reduced dramatically (Figure 13). Therefore, an important part of developing R-AUV systems and infrastructure will be to use sound system engineering principles. By clearly identifying, up front, the operational requirements and risks, systems will be developed with proper materials, minimal single points of failure, and well-defined interfaces between components.

Once deployed in remote ocean locations, the cost of intervening when a system component fails is extremely high because it will likely involve the mobilization of a surface vessel, ROV, and operators. To avoid premature failure, a robust system testing strategy must be adopted. Testing programs should begin in accessible locations, such as test tanks or pools, and move to locations that progressively resemble the final deployment location. Similarly, resident vehicle deployment duration should be increased gradually. For example, before attempting a year-long deployment, operations of weeks to months should be completed. Accommodating this level of progressive operations will require access to testbeds, and making the most out of each test phase will rely on intensive monitoring of subsystem performance.

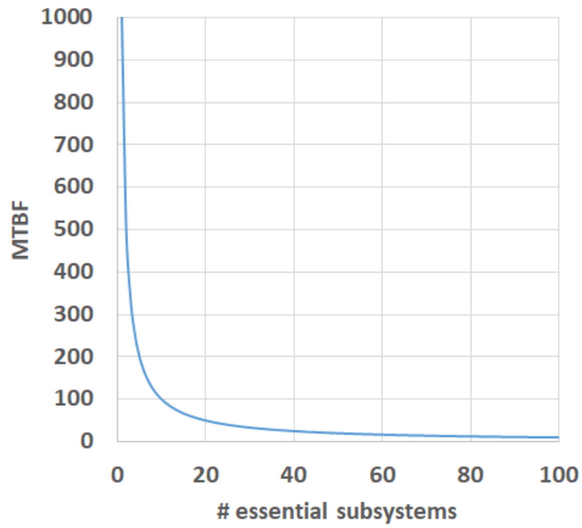

Figure 13. Generic plot of reduction in system mean time between failure (MTBF) as the number of essential subsystems increases.

Extreme Environments

To achieve close-up observation of some of nature's most energetic, mysterious, and transient events, some risks are unavoidable, like operating above an erupting underwater volcano or beneath a calving iceberg. Indeed, scientific breakthrough often results from operating in extreme environments, with the assumption of the inherent risk. These risks can be managed responsibly (though not diminished entirely) through operational planning and procedures. Vehicle self-awareness and smart behaviors may be able to minimize the impact of hazards on system operability. For instance, data collected by the OOI-CA at Axial Seamount may detect elevated levels of seabed motion as an eruption occurs, while acoustically-detected impulses may indicate explosions of lava at the seafloor. Not only will this information help to manage the operations of a resident vehicle into areas of scientific interest, such as the mid-water eruptive plume, but it can also be used to help the vehicle navigate around potentially dangerous conditions, like spewing lava. In addition, a complimentary suite of onboard sensors should be implemented to preserve vehicle safety. These may include obstacle avoidance sonars, hydrophones, or other proximity indicators that will help the vehicle steer around hazards.

Recommendations

R-AUVs are in their infancy, yet have the potential to dramatically alter the way in which we interact with, and understand, the subsea environment. With investment being led primarily by the offshore energy sector, maneuverable, docking vehicles are being developed for their promise to replace costly surface vessel and ROV operations. These same features and functions will enable research opportunities that were previously out of reach. With the ability to persist in remote locations for extended periods, R-AUVs will provide an adaptable and long-term means of interacting with and responding to the dynamic ocean environment. As industry moves forward with automated robotic vehicles, new autonomous capabilities will exist that have, until now, only ever been possible through vessel-based ROV operations.

Residency of mobile vehicles, however, presents an extreme technical challenge due to the remoteness of the ocean environment and to the critical importance of true vehicle self-monitoring and autonomy during operation. Therefore, testbeds and extensive system trials will be necessary to develop and prove the reliability of R-AUV systems. Ideally, testbeds will allow staged development, from highly accessible sites for early development to more realistic or relevant scientific and industrial proving grounds for more mature testing. Ideal testbeds will be accessible and will include infrastructure to communicate with and supply power to the vehicle dock, while remaining readily accessible and providing safeguards to protect vehicles under test.

Cabled observatories will be an excellent proving ground for R-AUV operations, as they can power docking stations and host communication links for vehicle data, allowing shore-based operators to track and adjust vehicle missions. In the long term, alternative energy scavenging power sources will enable remote, long-duration observing anywhere in the world.

Across each of the applications assessed during the May 2018 workshop, a common theme of the mid-water and seafloor observation breakout discussions was the diversity of missions that a R-AUV may address while on site; diverging sets of sensor needs may be addressed more efficiently with multi-vehicle or in situ payload module changes, while the basic functions of power transfer, communications, and navigation must be optimized for long-term deployments. Across applications, R-AUVs must also rely on autonomous processes to self-monitor and adapt to changing environmental conditions.

With the convergence of interest and technology across scientific disciplines, industry, and defense applications, the research community now has an opportunity to take a leading role in R-AUV technology development, and to leverage industry investment in R-AUV technologies that have the potential to improve societal understanding of some of the most remote and unexplored ecosystems on Earth and beyond.

Unattended deep sea autonomy in its many forms has huge potential, and the field is in its infancy. The inevitable convergence of artificial intelligence and the flow of real time, ocean based data types make it clear that this is a growth field with the potential to revolutionize the many ways in which humans interact with the planetary ocean.

Appendix A: List of Attendees

Kim Andrews	Joint Institute for the Study of the Atmosphere and Ocean and NOAA
Larry Atkinson	Ocean Observatories Initiative Facility Board
Christian Baillard	University of Washington
Ed Baker	NOAA Pacific Marine Environmental Laboratory
Tamara Baumberger	NOAA Pacific Marine Environmental Laboratory and Oregon State University
Monique Bell	University of Washington
Karen Bemis	Rutgers University
Katie Bigham	University of Washington
Justin Burnett	Applied Physics Laboratory – University of Washington
David Butterfield	University of Washington and NOAA
Jackie Caplan-Auebach	Western Washington University
Bill Chadwick	NOAA Pacific Marine Environmental Laboratory
Elizabeth Clarke	NOAA
Lisa Clough	National Science Foundation
Andrea Copping	Pacific Northwest National Laboratory
Tim Crone	Lamont-Doherty Earth Observatory, Columbia University
Thomas Curtin	Applied Physics Laboratory – University of Washington
Kendra Daly	University of South Florida
John Delaney	University of Washington
Annette DeSilva	University-National Oceangraphic Laboratory System
Daniel Dichek	Georgia Institute of Technology
Grant Dunn	Applied Physics Laboratory – University of Washington
Pierre Dutrieux	Lamont-Doherty Earth Observatory, Columbia University
Bob Dziak	NOAA
Peter Erkers	Saab
Norman Farr	Woods Hole Oceanographic Institution
Dehann Fourie	Massachusetts Institute of Technology
Erik Fredrickson	University of Washington
Lee Freitag	Woods Hole Oceanographic Institution
Ryan Frommelt	L3 MariPro
Christopher Gaudig	German Research Center for Artificial Intelligence (DFKI GmbH)
Chris German	Woods Hole Oceanographic Institution
Brian Glazer	University of Hawaii
Andrew Hamilton	Monterey Bay Aquarium Research Institute
Kevin Hand	NASA Jet Propulsion Laboratory
Rose Hilmo	University of Washington
Brett Hobson	Monterey Bay Aquarium Research Institute
Jim Holden	University of Massachusetts Amherst

Geoffrey Hollinger	Oregon State University
Bob Houtman	National Science Foundation
David Hume	DOE Water Power Technologies Office
Anatoliy Ivakin	Applied Physics Laboratory – University of Washington
Scott Jenne	National Renewable Energy Laboratory
Alex Johnson	International Submarine Engineering Ltd.
Carl Kaiser	Woods Hole Oceanographic Institution
Tim Kearns	Numurus
Deborah Kelley	University of Washington
Michael Kelly	Monterey Bay Aquarium Research Institute
Friedrich Knuth	Rutgers University
Wu-Jung Lee	Applied Physics Laboratory – University of Washington
Hui Qing Li	University of Washington
Trina Litchendorf	Applied Physics Laboratory – University of Washington
Martin Ludvigsen	Norwegian University of Science and Technology
Dana Manalang	Applied Physics Laboratory – University of Washington
Aaron Marburg	Applied Physics Laboratory – University of Washington
Benjamin Maurer	Applied Physics Laboratory – University of Washington
Ian McKissick	Sound and Sea Technology, Inc.
Craig McNeil	Applied Physics Laboratory – University of Washington
Dallas Meggitt	Sound and Sea Technology, Inc.
Matt Meister	Georgia Institute of Technology
Afshin Mesbahi	University of Washington
Kristi Morgansen	University of Washington
Anuscheh Nawaz	Applied Physics Laboratory – University of Washington
Jacqueline Nichols	Cellula Robotics Ltd.
Matthew Palanza	Woods Hole Oceanographic Institute and Ocean Observatories Initiative Coastal and Global Scale Nodes
Brendan Philip	University of Washington
Abi Powell	Lynker Technologies and Northwest Fisheries Science Center
Giora Proskurowski	MarqMetrix
Nicolaus Radford	Houston Mechatronics Inc.
Charles Rameu	Georgia Institute of Technology
Chris Roper	Saab
Fredrik Ryden	BluHaptics
Youngsrun Ryuh	RASTECH Co., Ltd.
David Schmidt	University of Washington
Jason Seawall	Numurus
Keith Shepherd	Canadian Scientific Submersible Facility
Madison Smith	Applied Physics Laboratory – University of Washington
Zhuoyuan Song	University of Florida

Michael Steele	Applied Physics Laboratory – University of Washington
Carol Stepien	NOAA
Andy Stewart	Applied Physics Laboratory – University of Washington
Richard Thomson	Fisheries and Oceans Canada
Andrew Thurber	Oregon State University
Jake Tompkins	Modus Seabed Intervention Ltd.
Ben Waters	WiBotic
Sarah Webster	Applied Physics Laboratory – University of Washington
Sheri White	Woods Hole Oceanographic Institution
Theresa Whorley	University of Washington
William Wilcock	University of Washington
Jason Williams	Schmidt Ocean Institute
Guangyu Xu	Applied Physics Laboratory – University of Washington
John Yamokoski	Houston Mechatronics Inc.
Lisa Zurk	Applied Physics Laboratory – University of Washington

Appendix B: Workshop Agenda

Wednesday, May 9 – Maple Hall Great Room, UW Campus

8:00 AM **Arrive** – Continental Breakfast

8:30 AM **Opening Remarks** – John Delaney, Lisa Clough, Larry Atkinson

8:45 AM **A Vision and Challenge for R-AUVs**
Dana Manalang

9:10 AM **OOI Cabled Array – Capabilities and Potential**
Deborah Kelley

9:20 AM **Axial Seamount – A Wired Window to Real Time Mid-Ocean Ridge Impacts on Overlying Oceans** (Focused 6-min talks)
J. Delaney – Overview. Seizing a historic opportunity: Axial wired and restless
Ed Baker – Eruptive plumes
Bill Chadwick – Inflation and long-range prediction of Axial eruptions
William Wilcock – Defining eruptive events: Before, during, and after
Guangyu Xu and Bill Lavalle – Modeling fluid flow in the Axial environment
Kendra Daly, Doug Luther, Rick Thomson – Water column studies of Axial Seamount
Jim Holden and Julie Huber – Microbial studies of the Axial system

10:10 AM **Enabling Technologies**
Ben Waters – Wireless power
Norm Farr – Optical communications

10:30 AM Coffee Break

10:45 AM **Science Applications for R-AUVs: From the Arctic to Outer Space** – Tim Crone
Pierre Dutrieux – R-AUVs for polar science: Why? Why not?!
T. Baumberger, B. Philip, M. Torres – The use of R-AUVs at gas hydrate and seep sites
Kevin Hand, Chris German – Oceans in our solar system
Brett Hobson – Open ocean Lagrangian microbial observatory

11:30 AM **Breakout 1**
What questions/problems can be addressed by a persistent, mobile system?
Mid-Ocean Ridge Eruptions – Seafloor and Water Column
Polar Science and Off-Planet Oceans
Gas Hydrates and Coastal Applications
Maintenance and Operation of Installations

12:30 PM Lunch

1:30 PM **Lightning Talks: Session 1**

2:00 PM **Speed Round – Vehicle Systems and Capabilities** (5–10 min/station)
Payload/Sensors
Navigation
Docking
Power
Communications
Human–Robot Interface and Autonomy

3:00 PM Coffee Break

3:30 PM **Breakout 2**
Concept of Operations

5:00 PM **Group Discussion**

5:30 PM **Adjourn**

6:00 PM Networking Reception (909 Boat Street)

Thursday, May 10 – Maple Hall Great Room, UW Campus

8:00 AM **Arrive** – Continental Breakfast

8:30 AM **Breakout Group Reports**

9:00 AM **Panel: Strategies and Tactics for R-AUV Deployments** – Dana Manalang
Jake Tompkins
Andy Hamilton
Carl Kaiser
Andy Stewart
Geoff Hollinger

10:30 AM Coffee Break

10:45 AM **Breakout 3**
Functional Specifications and Vehicle Mission

12:00 PM Lunch

1:00 PM **Lightning Talks: Session 1**

1:30 PM **Agency Commentary**
How does R-AUV development and installation fit with current and future funding priorities? (NSF, NASA, ONR, DOE, NOAA)

2:00 PM **Breakout 4**
Identifying and Bridging Gaps

3:00 PM Coffee Break

4:30 PM **Breakout Group Reports and Discussion**

5:30 PM **Adjourn**

Friday, May 11 – Hardisty Conference Center, APL-UW Henderson Hall

8:00 AM **Arrive** – Continental Breakfast

8:30 AM **Summary of Major Themes**

9:00 AM **Group Discussion**
Testing strategies (systems, test beds)
Next steps? Funding sources and strategies, partnering
Framing the workshop report

10:30 AM Coffee Break

10:45 AM **Preliminary Writing** (one paragraph per attendee)

12:00 PM Lunch

1:00 PM **Report Writing**
Organizing team and interested contributors

4:00 PM **Adjourn**

Appendix C: Speed Round Tables

Docking Systems

Docking subsystems	Today	Future	How to get there (R&D, integration, test)
Vehicle/dock alignment and coupling	Cone dock	ASV retrieval	Mechanical transfer from vertical velocity from chronic venting
Data transfer to vehicle	Remus LC/LR	Machine vision and AUVs	Robust, self-contained, relative navigation (acoustic/magnetic/visual)
Power transfer to vehicle	Mechanical cabling — mm-range inductive and cm-range adaptable resonant	Power sharing	Landing pad/nest; not nose cone
Biofouling coating and protection	Optical communications	Smart docks	
Hydrothermal plume fouling	Biofouling cleaning	Sample analysis capability	
Biofouling cleaning and removal	Space vehicle autonomous docking	Modular exchangeable batteries	
Data transfer to shore	Vicinity docking; taking dock to AUV	Mobility of docking station; ease to deploy	
Deployment and recovery (self-ballasting)	Moving mother ship	Docking station that can be manipulated (ROV)	
Keep critters out		Air support	
		Dry dock underwater	
		Alternative power: wind, solar, hydrothermal	
		Docking to ASV	
		Array of docks around feature or across margin	
		Power at sea from wave power	
		AUV–AUV docking for cooperative exploration (data transfer)	
		Vehicle cleaning and maintenance, e.g., with ROV on node	
		Replenishment of sampling equipment or supplies; replacement parts	
		Prototype sensors test bed	
		Sample storage	

Power Sources

Technologies	Today	Future	How to get there (R&D, integration, test)
Shore-based cable	8–10 existing	RTCs	DOE funding
Solar	Highly expandable minerals passing through thermocline, driving electric motor	Power sharing	Leverage FDECO
Wind	Subsystem power management	Prioritize efficiency	R&D distributing computation as allowed by communications ‘low and slow’ frameworks
Wave	Rate of battery discharge?	Long-term deployments: margin-scale, week-long	
Stored		Modular exchangeable battery packs	
Diesel		Safer lithium-like batteries	
Fuel cell		Replaceable fuel cell components on vehicles	
Hydrothermal		Prevent energy storage degradation	
		Docking on thermal heat sources	
		Subsea bio-digester for algae biofuel and power	
		Aluminum seawater and fuel cells	

Sensor Systems and Payloads

Sensor Types

Dissolved O_2

Temperature

Salinity

Nutrients (NH_4, NO_3, NO_2)

Vemco fish tags

Dissolved gases (any) – methane

pH

CO_2

Turbidity

Oxidation reduction potential (ORP)

Trace Metals

Environmental Sample Processor (ESP)

Multibeam sonar

Microstructure

Camera with strobes (~12 Mpx)

Stereo video imaging

Camera imaging systems

Hydrophone

ADCP

DVL

Fiber optic gyro (FOG)

IMU

Mineral/microbe spectroscopy (VNIR)

Mass spectroscopy in situ (organic and inorganic)

Chemical mapping

Communications

- Automatic identification system (AIS) receiver/transmitter
- Acoustic modems
- Iridium/satellite communications (clear view needed)
- Wireless high-bandwidth communications and control

Sensor challenges	Vehicle/SW/ data issues	Future needs	How to get there (R&D, integration, test)
Must be stationary for minutes Biofouling Calibration/ auto-calibration Time sync Time stamp Acoustic interference Reducing/preventing cross-talk	Vehicle design with focus on adaptability Sensor-reactive software Sampling optimization strategies Estimation algorithms Data fusion Big data Quiet vehicles for hydrophones	High-accuracy, low-drift, fast-response sensors Miniaturized sensors Low-cost sensors Distributed sensors High-efficiency sensors Low-power sensors Sensor networks for distributed sensing Fleet of R-AUVs Compartmentalized, exchangeable sensors Capability to move an instrument on the seafloor Deploy navigation beacons Sensor types: • Stab sensor on manipulator arm • Sediment core sampler • Physical water sample collection, filtration, preservation • Return of physical samples • In situ incubation for water/microbe samples • Solid state chemical sensors • 3-D laser scanner • Particle imagery • DNA recognition • DNA and RNA sample preservation • In situ gene sequencing for DNA and RNA • Water column organisms and full nutrient suite • Identify and sample species groups (biology) • Save full water column multibeam sonar • Sub-seafloor imaging (2D and 3D seismics) • Heat flux • Iron, methane, hydrogen • Inverse polarization	Incentives for development (funding agencies, Xprize) Formalized research/lab networks Dedicated test facilities Double the NSF OTIC budget Leverage consumer and prosumer electronics Productionization Standards!!! R&D on processing, fusing in spatial understanding of all

Communications

Technologies	Today	Future	How to get there (R&D, integration, test)
Shore-based cable Satellite Acoustic Optical Radio frequency line-of-sight Global System for Mobile (GSM) Comms Long reach (LR) fiber	Low bandwidth High latency Single hop acoustic Astrium Services as data relay Short range Low-cost/low-bandwidth acoustic Very short range Data compression Data piracy Onboard processing Auto-release data buoys Onboard storage A gap in acoustic ranges, high-bandwidth short range	Connect to AUV during survey Security Ad-hoc acoustic mesh network Match capabilities: communications, data, power Data management Communications rating protocols More autonomy for high-level autonomy C^2 Subsea data mining Interference: optical, satellite, acoustic Large dataset transfer: multibeam, video. Transfer subset until vehicle is close enough? Desire to download all recorded sensor data at each dock station visit RF underwater Spread spectrum acoustic communications Semaphore code (gesture based) Use diff paths (more bandwidth) Enough to transmit high-resolution (12 Mpx) photo mosaic images at end of mission Cheaper connectors Ruggerized fiber optics Cheaper interconnect In-depth ocean imaging as well as satellite imaging Intelligent filtering Transferring mapping estimates between multiple agents. How to communicate the uncertainty efficiently?	Observatories as test beds R&D in simultaneous localization and mapping Derived products Cabled observatories as test bed

Navigation

Methods	Today	Future	How to get there (R&D, integration, test)
Dead reckoning Inertial navigation Environment-based navigation Ultra-short baseline Long baseline Terrain-based navigation Local power for persistent operation	Doppler velocity navigation (seafloor) Expedition/ship Long-range homing (100s km) Terrain relative navigation Acoustic imagery mapping over time Flow aided navigation	Use ADCPs or alter current meta (velocity sensors) cm and mm accuracy of observations (seafloor spreading, deep morphological changes) Gravity Use local magnetic field variations Inverted USBL Multi-vehicle cooperative Real time navigation command and control from shore Repeatable +/– 1 cm In-depth real time satellite data images and video of both land and ocean-based systems How do you locate small targets in a large space? Sub-meter accuracy for revisiting 0.25 m^2 locations One-way travel time USBL Good for mild water column density Self-navigating mid-water AUV Passive receiver — mobile; active transmitter — stationary	Automated on-vehicle processing for map generation Optics Visual odometry in low-light and turbidity Plenoptic camera Automated bathymetry processing Track animals tagged or passive Leverage multi-sensor technique from heterogenous data INS/magnetics/acoustics/gravity/etc. Generic dynamic models with adaptive parameter ID Absolute vs. relative accuracy (good prevision/bad accuracy) Need to lower equipment costs Meshed node network Non-Gaussian multi-sensor, factor graph based data fusion/in-situ/real time Across platforms (UAVs, animals) Self-deployable relocatable expansion to LBL Development platforms with access to source code

Human–Robotic Interaction and Autonomy

Operations	Today	Future	How to get there (R&D, integration, test)
Mission planning Event response Expanding to ROV tasks Real time navigation and manipulation Need for autonomously knowing how to identify hydrothermal plumes and how to adapt survey strategies Levels of autonomy Transition from more to less autonomy (and reverse) Cyber security How to know if AUV did desired task? Support vessel tracking Large geographic separation between robot platform and operators Fast data review post mission	Re-tasking Real time data streaming (chemical) Adapting in situ (re-planning) Lock step style and narrow application space navigation solutions Lower risk and cost Data telemetry easily interrupted Ground truthed adaptive sampling tests: temperature, ORP, pH, CSS, etc. to trigger filtration Reaching human consensus via telepresence (+ latency)	Recovery from faults Non-Gaussian capable sensor fusion for more robust navigation Identify when the AUV needs help decoding something (classification) Flip correspondence between human operators and robotic platforms: from many operators to one robot to many robots to one operator Subsystem health assessment and fault response Acoustic based sampling and manipulation Self-repairing via carbon removal from ocean Iridium next game changer Real time map generation and streaming Learning and AI-based bandwidth measurement Automated response to chemical/physical signals to direct sampling Deep learning Non-deterministic operations Remote control to collect biological samples using real time camera feed Respond automatically to chemical anomalies by taking physical sampling and photo survey Many heterogeneous vehicles controlled by one operator Autonomy through communication restrained resources VR operation or exploration of sensed working zone Autonomous mission re-planning and prioritization	Engage autonomous verification community Leverage open-source projects and partnerships User testing and studies Multi-agency funding efforts Research on blended human and machine autonomy systems Redundancy/cross-check Privacy and security

Operations	Today	Future	How to get there (R&D, integration, test)
		Automate tasks: sampling, measurement, hovering, transit, mapping	
		Automated mission planning based on real time sensor data analysis	
		Inter-platform communication systems: USV to AUV	
		Mission prioritization/coordination among array of AUVs	

Appendix D: Selected Bibliography

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