Integrating Science Needs with Advanced Seafloor Sensor Engineering to Provide Early Warning of Geohazards: Visioning Workshop and Roadmap for the Future

Final Report for NSF Grant No. OCE-1817257

13 June 2019

Christopher E. Parrish, H. Benjamin Mason, Anne M. Trehu, Geoffrey A. Hollinger, John S. Selker, and Eugene Zhang

***See Appendix B for other workshop participants**

1. Introduction

The widespread lack of seafloor and subseafloor data continues to present a significant impediment to our understanding of the oceans, particularly with regard to investigation, modeling, detection, and early warning of geohazards. Sensors designed for land-based applications (e.g., GPS, solid state sensors, and optical sensors) continue to evolve rapidly, but are often poorly suited to the high-pressure, corrosive, low-temperature, and optically-opaque ocean environment. Although specific, localized counterexamples exist, current seafloor and subseafloor sensors and related ocean observing infrastructure generally suffer the following drawbacks: extensive cabling requirements, lack of real-time (or even near-real-time) data necessary for applications such as geohazard monitoring, low bandwidth, lack of autonomy, short maintenance cycles, a lack of spatial coverage and resolution, and high cost. The preceding limitations can only be addressed through synergies between the scientific and engineering communities.

A number of ocean observing networks/systems have been developed and deployed, including the Ocean Observatories Initiative (OOI) Cabled Array (previously known as U.S. NEPTUNE: North-East Pacific Undersea Networked Experiments) (Barnes et al., 2007; Kelley et al., 2014), NEPTUNE Canada (Barnes et al., 2007), DONET (Dense Oceanfloor Network system for Earthquakes and Tsunamis) (Kawahuchi et al., 2008), VENUS (Victoria Experimental Network Under The Sea) (Taylor, 2009), MACHO (Marine Cable Hosted Observatory (Chen et al., 2012; Hsiao et al., 2014), and ESONET-NoE (European Sea Observatory NETwork – European Network of Excellence) (Puillat et al., 2009), among others (Favali et al., 2010; Favali et al., 2013). Although the expanding ocean observing infrastructure continues to extend capabilities, with respect to the scientific priorities addressed above (i.e., subduction margins and associated hazards and fluid flow in subduction margins), critical gaps still remain.

The most widely-recognized limitation is spatial coverage, including both the footprint of the monitored region and resolution within that footprint. It is estimated that orders of magnitude greater coverage is required to measure geodetic deformation offshore (Wilcock et al., 2012), and, as an added challenge, the greater coverage may need to be achieved without cables because of the cost of cables and their susceptibility to damage within the harsh seafloor environment. However, increasing spatial coverage of existing seafloor sensing infrastructure is far from a complete solution. Beyond spatial coverage, additional engineering challenges exist, including the ability to collect data in near real-time from a large number of sensors distributed over a large area. Additionally, the environmental footprint of seafloor sensors remains a concern.

Addressing the aforementioned science questions and technical limitations requires new, intelligent, autonomous, and agile seafloor sensor technology. Hindrances to the design of robust and reliable sensors for use in the seafloor environment include the corrosiveness of saltwater, as well as difficulties in servicing the sensors. Nevertheless, emerging technologies offer hope that viable solutions are on the horizon. Sensor technology is continually advancing to enable longer-term monitoring and data with better resolution and accuracy. In parallel with sensor development, advances in data acquisition and transfer methodologies are being developed that will enable real-time monitoring for time-critical applications such as earthquakes and tsunamis.

In recognition of these challenges and opportunities, a seafloor sensors workshop was organized to bring together leading experts within key fields in engineering and ocean science and representing the academic, government, and private sectors. The objective of the workshop was to understand the present state-of-the-art and then chart the future for instrumenting the seafloor to provide real-time data measuring dynamic deformation of the seafloor on multiple scales, from the large scale deformation resulting from a major interplate earthquake to more localized deformation due to a major slope instability.

The workshop was funded by the National Science Foundation (NSF), OCE Division of Ocean Sciences (Award # 1817257). This report summarizes the key findings, outcomes, and recommendations of the workshop and serves as a draft of the comprehensive roadmap.

2. Workshop Summary

The workshop was held at the Salishan Resort conference center (Fig. 1) in Gleneden Beach, Oregon, on July 12-13, 2018, and brought together 64 participants, representing 34 different organizations from academia, government, and industry, as well as a range of engineering and scientific disciplines (Appendix B). The two days of the workshop were organized such that most of the presentations were scheduled for the first day, while the second day was devoted primarily to brainstorming and group discussion.

Figure 1: Seafloor Sensors Workshop in Gleneden Beach, Oregon, July 12-13, 2018.

The workshop was designed to address four underlying questions, as follows:

<u>Day 1</u>

- Q1: What are the science needs for seafloor sensing?
- Q2: What can current state-of-the-art technologies deliver?

- Q3: What are the gaps between what currently exists and what is needed?

Day 2:

- Q4: How do we bridge the gaps?

In addition to the four questions listed above, another overarching theme for the workshop was managing environmental impacts for seafloor sensing. The remainder of this report is structured to sequentially address these overarching themes/questions. Appendices A and B contain the final workshop agenda and a list of participants, respectively.

3. Science Needs for Seafloor Sensing

Based on our workshop organization, and our pre-stated workshop goals, four overarching science needs came to the forefront of our discussions during the workshop (Table 1).

Table 1: Science Needs

1. **Furthering our understanding of past and future earthquake and tsunami hazards using seafloor geodetic and seismological observations;**
2. **Predicting submarine slope instability by using subseafloor fluid pressure and permeability measurements;**
3. **Measuring seafloor venting and biologic activity on and beneath the seafloor;**
4. **Furthering our knowledge of climate change by measuring sea level, ocean temperature, and water chemistry**

Workshop attendees also discussed societal and commercial needs for seafloor sensors related to the four primary science needs listed above: 1) anticipation, detection and early warning of natural disasters originating offshore (e.g. earthquakes, tsunamis, slope instability, volcanic eruptions, and severe weather); 2) long-term environmental monitoring of off-shore regions; and 3) ocean energy and resource exploration and production.

The workshop participants brainstormed a list of the types of measurements, as well as related issues of deployment, stability, spatial and temporal scales, data delivery and management, that are needed to meet the science and societal needs summarized above:

- Absolute pressure on the seafloor and its use a geodetic measurement of elevation
- Transient ground displacement, velocity, and acceleration
- Seafloor tilt as a geodetic measurement
- Maintenance of timing accuracy to 1 ms or better over long time periods without continued access to a continuous GPS signal

- Water velocity near the seabed and through to water column to separate oceanographic from geodetic signals
- Temperature near and beneath the seafloor
- Salinity
- Density and stiffness of sub-seafloor sediments
- Methane content (dissolved and as bubbles of free gas) of the ocean and sub-seafloor sediments
- Ocean and porewater salinity, pH, oxygen content, etc.
- Biological measurements

While real-time data are not needed for many scientific investigations, they are essential for applications of the science to the development of earthquake, landslide and tsunami early warning (EEW, LEW, TEW) systems (Table 2). Clearly, latency is a primary consideration for early warning, and existing networks are generally regarded as being too slow. Some of the requirements for EEW and TEW were summarized in presentations at the workshop by D. Melgar and D. Schmidt, who also specified ~50 km station spacing for interseismic deformation monitoring, ~30 km station spacing for transient slow-slip events.

Table 2: EEW and TEW requirements, from workshop presentation of D. Melgar (Melgar, 2018).

Requirements	**EEW**	**TEW**
Sensor type (sample rate)	Strong motion (100Hz) Broadband (100Hz) Strain (≥ 1Hz) Acoustic GPS (>1Hz) Absolute pressure (≥ 1Hz) Hydrophones? (1kHz?)	generally the same as for EEW, but with less stringent constraints on data latency, etc.
Latency (includes packet size)	<2s	<30s
Sensor spacing	30-50km	50-100km
Time until onset of hazard	10-60s	5-15mins

4. Current State-of-the-Art Technologies

While not comprising a complete solution, it is important to note that a number of current and emerging technologies hold promise for addressing the science needs identified above. These technologies can be broadly grouped into the following classes: 1) autonomous vehicles/sensing platforms; 2) geophysical sensors; 3) chemical and biological sensors; 4) communications technologies; 5) data compression and analysis technologies (including visualization); and 6) power sources/energy harvesting technologies.

In the area of autonomous vehicles/sensing platforms, some recent advancements noted in the workshop include: automated vehicle guidance, and navigation (Mora et al., 2013)3D reconstruction and mapping (Li et al., 2018), human-vehicle interfaces and decision support

(Gomes et al., 2013), semi-autonomous underwater ROV (Fig. 2) unmanned deployment schemes, (Lawrence et al., 2018) ultra-short baseline (USBL) positioning systems, (Rypkema et al., 2017) global navigation satellite system (GNSS) aided inertial navigation systems, and long-duration autonomous underwater vehicles (both propeller-driven and buoyancy-driven (Bachmayer et al., 2004)). A key emerging technology is the capability for ROVs and AUVs to have "resident" capabilities where they remain in the ocean environment for long durations by recharging and communicating at docking stations. Such docking stations could potentially utilize marine renewable energy technologies for power (Strom et al, 2018).

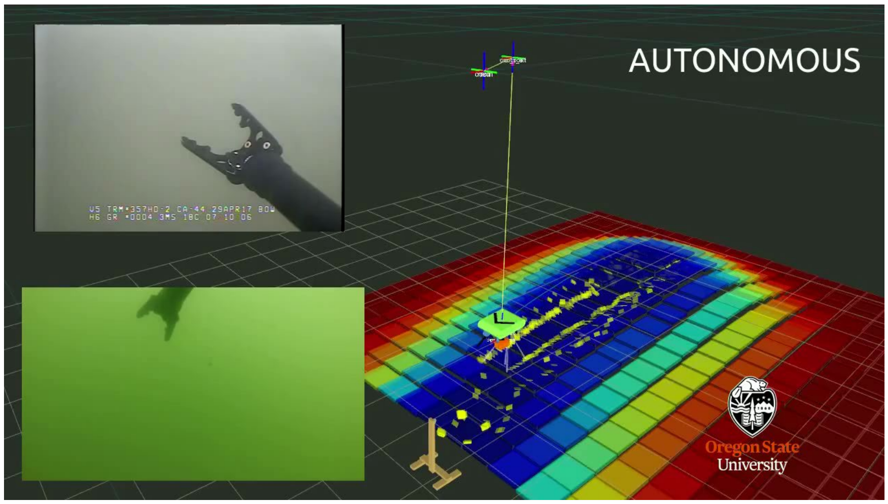

Figure 2: Semi-autonomous underwater ROV in an offshore intervention trial from workshop presentation of G. Hollinger (Hollinger, 2018).

Geophysical sensors are advancing on several fronts. Considerable attention has been focused in recent years on obtaining absolute pressure measurements on the seafloor for use in monitoring seafloor uplift and subsidence. Long-term drift has traditionally been a problem with these sensor, limiting their use for seafloor geodesy, but several approaches have been proposed to address this problem (e.g. Sasagawa and Zumberge, 2013).Paros reported on recent promising field tests the A-O-A method to calibrate absolute seafloor pressure sensors.

Use of optical fibers to sense strain, sound and temperature is another promising technology, both onshore and offshore, for obtaining measurements with high spatial and temporal density measurements of temperature, strain and acoustic signals. Nate Lindsey reported on recent experiments to use optical fiber to record seismic waves.

Progress was also reported by Kim Swords on technologies for transmitting sensor data to the surface, such as acoustic monitor transponders (AMTs), pressure monitor transponders (PMTs). Other promising sensing technologies for seafloor use include: MEMS gravimeters (Middlemiss et al., 2017); structure from motion (SfM) processing applied to optical imagery of the seafloor; lidar (laser scanning) for AUV navigation and seafloor mapping, satellite-based radar, emerging bathymetric sensors (acoustic and optical) during aftershock sequences to detect changes in the seafloor, and advanced optical sensors, including hyperspectral imagers.

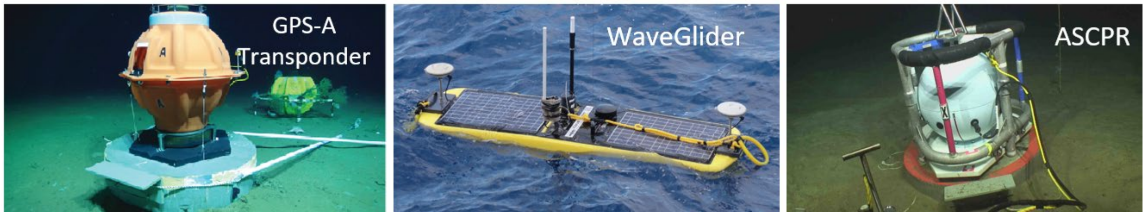

Figure 3: Current seafloor sensors, from workshop presentation of D. Schmidt (Schmidt, 2018).

Chemical and biological sensors are somewhat outside the scope of this workshop, but were considered for two reasons: 1) they can assist in assessing the environmental impacts of seafloor sensing systems, and 2) advancements made in chemical and biological sensors may be adaptable to geophysical sensors. Notable advances include those in the areas of micro fluid chemistry, ring-down spectroscopy chemistry. Phillip and Solomon reported on progress with seafloor fluid flow and chemical sensors.

In the area of communications technologies, advances are occurring in the areas of optical communications, acoustic communication (up to 3.5 Kbps), data delivery network and wireless communications, global, low-cost surface-to-sky communication, and surface to ground communications via satellites. Underwater wireline networks advances include those in tethered systems (cabled arrays) and smart cables (trans-ocean telecommunications systems). Meanwhile, underwater wireless communications advances include those in acoustic (Zheng et al., 2018; Singer et al., 2009), optical (WHOI, 2010; Kaushal et al., 2016), and magneto-inductive communications (Ahmed and Zheng, 2018; Sun and Akyildiz, 2012). Deep-sea to surface communications include long-range acoustic communications, and AUV+ short-range communication.

Emerging data compression and analysis technologies include notable advancements in the area of visualization, including cave automatic virtual environment (CAVES) (i.e., 3D immersive environment), portable/low-cost VR technology (e.g., for underwater landslide analysis and visualization of repeat bathymetry). Recent advances in data visualization makes it likely that soon we may have the capability of real-time, in-situ data analysis using the state-of-the-art topology-driven flow and tensor field visualization (Palacios et al., 2016; Zhang et al., 2009; Chen et al., 2007). In the realm of power sources/energy harvesting technologies, notable advances include those in ultra-low power data systems, data assimilation (satellite/ground-based) for detection of deformation and shaking wavefields (Melgar, 2018).

In addition, a few technologies were discussed that do not fall into the categories listed above but hold significant promise for advancing seafloor sensing. These include 3D printing to generate parts and devices that are cost-effective and durable on the seafloor, as well as advances in deep learning (e.g., convolutional neural networks).

The advancements along all of these dimensions over the past several decades are characterized in Figures 4-5, from the workshop notes of J. Selker. Oceanic applications have vastly differing requirements for resolution and budgetary restrictions. For example, navigation in the ocean is rarely needed at the sub-meter level, thus early GPS systems largely satisfied this demand in the early 1990's with technologies that could be classified as having 1 ppm resolution (i.e., 1 m out of 1,000 km). To detect ocean floor subsidence required accuracy of depth measurements that were on the order of 5 cm in an ocean with depth of on the order of 5 km with accuracy over 1,000 days, which could be characterized as 0.01 ppm-day resolution. To accurately monitor climate-change driven sea level change requires a sensor that has 0.05 mm stability over decadal period, which translates to 0.01 ppb-decade resolution. As instrumentation evolves in time, cost-performance thresholds are surpassed which open new opportunities for observation to address the most demanding objectives.

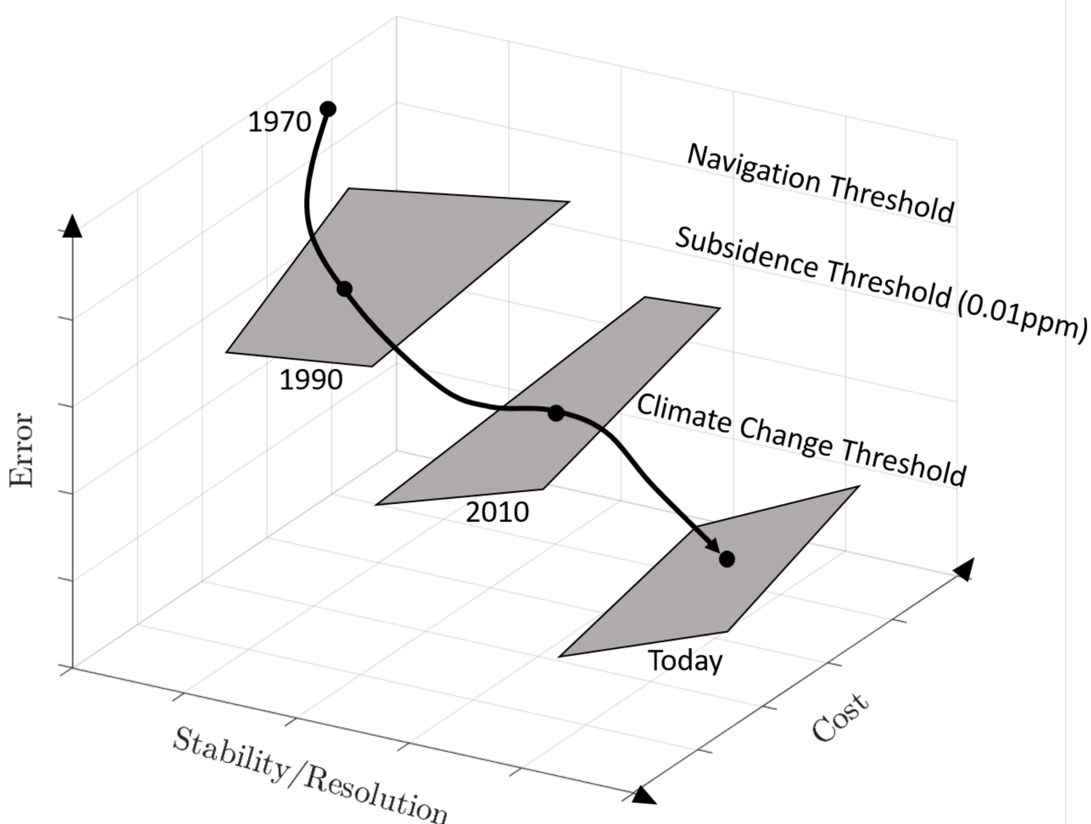

Figure 4: Schematic depiction of the evolution of sensing along the dimensions of uncertainty (or error), cost, and stability/resolution over the past half century.

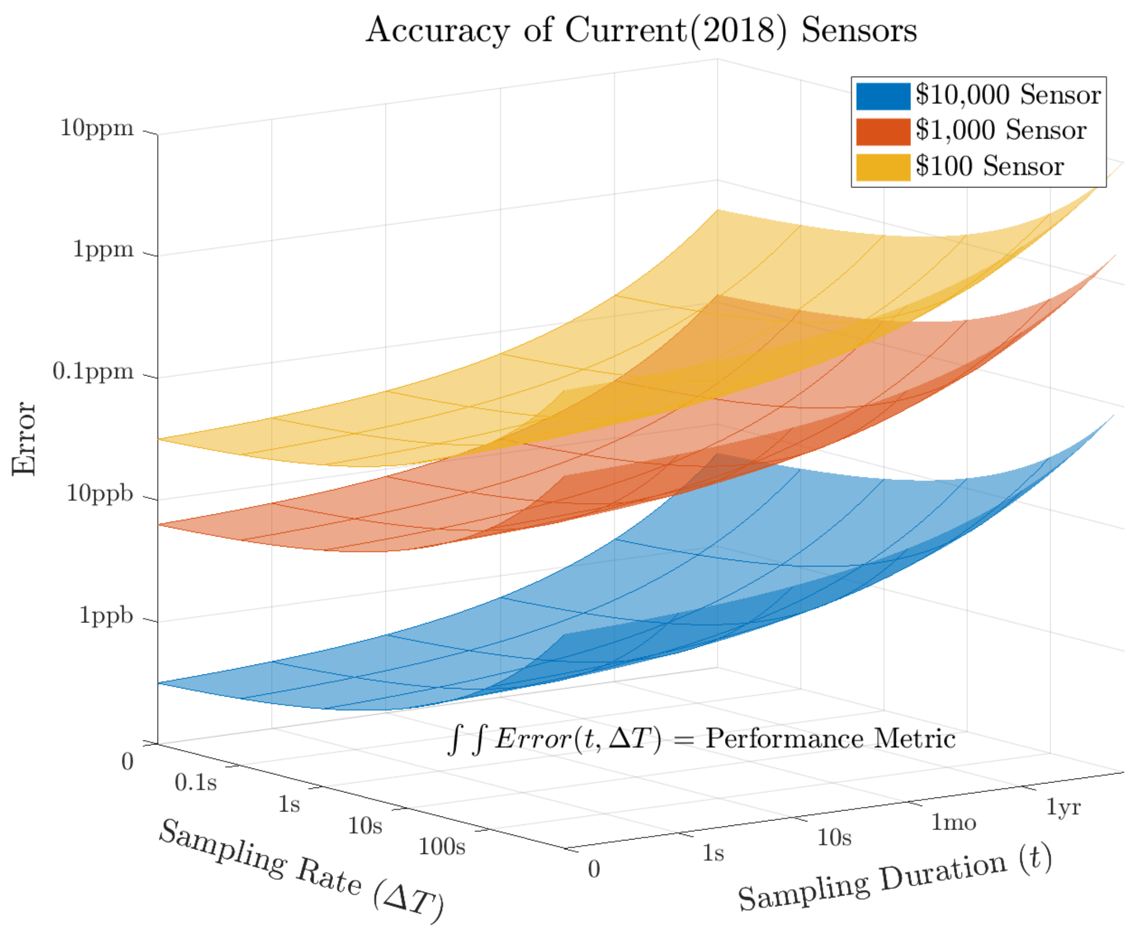

Figure 5: Sensor performance must be considered as a multi-dimensional tradeoff between price, accuracy, stability, and sensitivity. Here we illustrate that technological advancement can be characterized by computing the volume under this performance surface for each price point (here lower volume indicates better performance). With MEMs sensing being developed for consumer applications, it is believed (but not definitively shown) there has been a nearly universal narrowing of the integral sensor cost per performance which has lagged in its penetration of the oceanographic market. (Note: this plot is intended to be conceptual, and may not reflect the performance of any specific, commercially-available sensor.)

5. Sensor Needs and Technology Gaps

The workshop participants brainstormed sensor needs and technology gaps based on science needs and types of needed measurements, which are shown Table 3. It was acknowledged that improving sensor quality while reducing the development and deployment time and decreasing cost and environmental impact are formidable scientific tasks that will require significant financial investment.

Table 3: Sensor Needs and Technology Gaps

1. **Improving the quality of seafloor sensor measurements** 2. **Creating new sensors and deploying them as quickly as possible** 3. **Improving the cost-effectiveness of seafloor sensors** 4. **Making the sensors environmentally benign (or environmentally helpful)**

The workshop participants explicitly discussed the following sensor needs and technology gaps:

- Seafloor sensors must be robust (i.e., able to withstand harsh environments)
- Seafloor sensors must be easily deployable and positioned (and re-positioned)
- Real-time (or near-real-time) two-way communication between sensors and with the surface is essential for many applications.
- Data storage needs must be determined based on the data collection protocols, and data storage should be improved to allow for longer-lasting sensors.
- Seafloor sensor longevity should be improved (i.e., appropriate power; data collection; sensor robustness).
- In many cases (e.g., sensing for geophysics applications), seafloor sensors arrays should be both dense, to avoid spatial aliasing, and have a large footprint, to capture the scale of the phenomena of interest.
- Seafloor sensors should have appropriate sampling rates to record the frequencies of interest without aliasing.
- To improve the cost-effectiveness of deployment and data collection, collocation of different seafloor sensors is recommended when logistically possible and scientifically justified.
- Seafloor sensors should be as cost-effective as possible.
- The environmental impact caused by seafloor sensors (during the deployment as well as during any maintenance missions and after the sensor service life ends) should be minimized.
- Whether it is more cost-effective and/or environmentally sound to develop disposable or reusable sensors should be evaluated.
- Sensors should be self-calibrating.
- The quality of the clock depends on the timing accuracy needed; for some applications, current clock drifts can be a factor limiting deployment duration or data quality. Chip-scale atomic clocks may be a solution for some applications.
- When instrument noise, rather than environmental noise, defines the noise floor at times of low environmental noise, efforts should be directed to decreasing instrument noise.
- Enhanced resolution is needed (e.g., nano-sensor technology compared to old DART system)
- Instruments must be designed and tested to ensure that sensors are well coupled to the environment (e.g., soil-sensor interaction for seismic and geodetic sensors, coupling to the sediments for temperature sensors)
- More reliable data transmission approaches are needed for seafloor sensors deployed in steep or rough terrain.
- Spatial distribution of sensors should be sufficiently dense to meet a range of science needs and should be determined as a factor of bathymetric slope. Signals can largely be

filtered in relatively flat environments; slopes are an ongoing problem as the signals are much more complex and will require much denser instrumentation. Additionally, steep slopes can be a problem for data telemetry to the sea surface or land.

An overarching consideration is that sensor needs are highly dependent on the particular science application, which necessitates defining broad ranges or classes of requirements. For instance, in some cases, sensors need to collect data for five to ten years or more to be useful for science, whereas in other cases, days of collected data would push science forward (see Sections 4 and 5). Similarly, the sensor footprint size is highly-dependent on the science application. In many cases, scientists will need to pick the most important requirements at the expense of others, to make the sensor production possible. These challenges can be alleviated through enhanced coordination between sensor manufacturers and scientists, better understanding of design tradeoffs, as well as sensors and associated software that are designed to be modular and reconfigurable.

A common theme across the discussion of current challenges relates to the need for better in-situ calibration methods. Currently, the precise measurements needed for geohazards research can be swamped by sensor noise and drift and by other environmental processes (e.g. ocean currents and wave generate "noise" that can hide signals due to geodetic seafloor deformation).

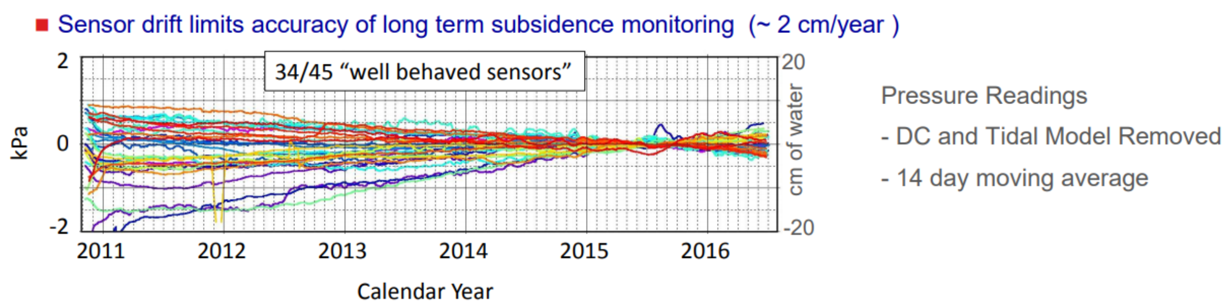

Figure 6: Long-term stability of pressure sensors, from workshop presentation of K. Swords (Hatchell et al., 2018).

Another persistent theme relates to limitations of current underwater communications technologies. It is noted that radio frequency (RF) has major limitations: it is limited in bandwidth (1 MHz) and has very short range (< 1 m). Other technologies are viable, but significant tradeoffs exist between bandwidth and range. Magneto-inductive (MI) communications have small bandwidth (<500 kHz) and short range (~100 m); optical beams afford large bandwidth and short range (20 - 200 m). Meanwhile, sound propagation (AComm) affords short (< 1 km), medium (1 - 10 km), or long range (1000 km), at 300 kHz (HF), 10 - 100 kHz (MF), and < 2 kHz (LF), respectively, as depicted graphically in Fig. 6 (Zheng, 2018).

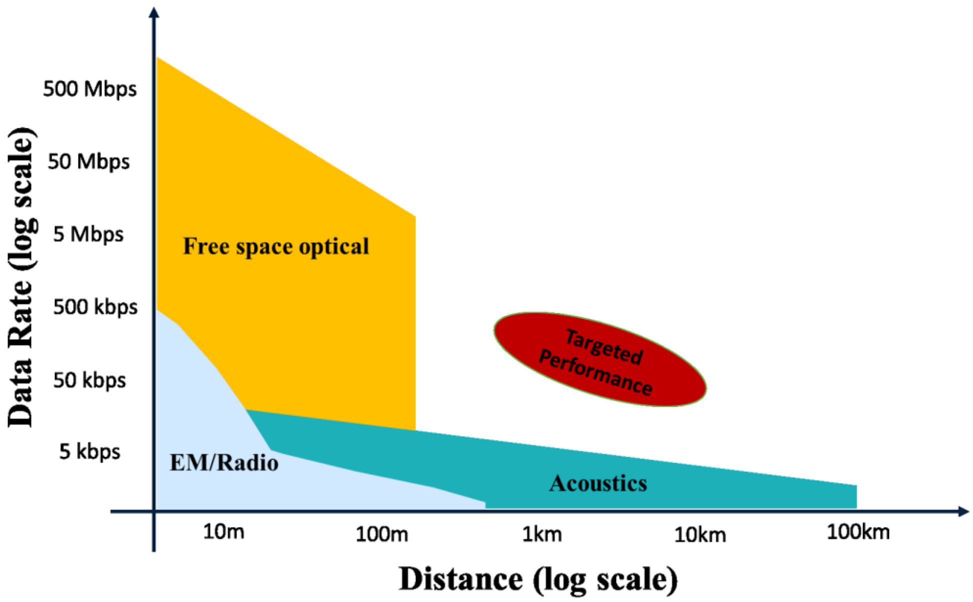

Figure 7: Limitations of current underwater communication means, and desired performance for medium-range wireless communications, from workshop presentation of R. Zheng (Zheng, 2018).

6. Bridging the Gaps

Three general strategies for bridging the technology gaps were discussed: 1) adaptation of existing, terrestrial sensors for use in the ocean; 2) improvement of existing seafloor technologies; and 3) advancement of supporting technologies to enhance the utility of existing sensors/networks and improve our ability to derive useful information from them.

6.1. Adapting terrestrial sensors for underwater use

- Understanding and mitigating the effects of seawater on the sensors (e.g., corrosion)
- Understanding and mitigating the effects of pressure (e.g., surface-mount resistor failure at depth)
- Leveraging the types of advanced imaging being developed for subaerial landslides and extending them to submarine landslides
- Leveraging recent advances in photo-optical sensing, including low-power, consumer-grade sensors with the potential for mass-deployment on the seafloor

6.2. Improve existing underwater technologies

- Feedback to industry/instrument providers
- Facilities to meet time frame needs for instruments, particularly following an earthquake
- Alternate technologies for water column properties besides CTD measurements?
- Vertical arrangement cosmic ray muon detectors
- Vertical DTS data; seafloor systems

- Observing the environment itself: organisms respond to physical and chemical stressors in ways that might be observable; medical field uses nano sensors to measure strain for blood flow
- Redox potential, polysaccharides, etc.
- Need robust power budgets for any technology we are considering; make producers aware of maximum power budget
- Are there new technologies in the consumer realm that we could take advantage of to improve power costs in our realm? Need to engage engineers in those communities; challenge them to meet our needs; collaborations and community are critical - it does not make sense to re-create technologies that already exist
- Modernized data logging system: would take a significant investment (NSF), but would provide many advantages
- Cable systems - power and bandwidth; why not instrument nodes on the smart cables?
- Leveraging fiber optic cables on the seafloor (major discussion point)
- Wave energy harvesting
- Manage time for the power budget - waking instruments, calibrations, triggering

6.3. Development/enhancement of supporting technologies

6.3.1. Robotics

- Navigation for AUVs; sensor location/moving over time; external markers/beacons, feature-based localization, USBL might not perform in noisy environments
- Quick identification of multi meter displacement on the seafloor for hazards applications; instant confirmation an event just happened; could some of the technology from an AUV be mounted on a monument for a clear, fast indicator?
- Costs are a consideration, especially as numbers increase; buoys are cheap
- Autonomous surface vehicles - challenges in classification (vessel vs flotsam)
- Drone-like instruments with high bandwidth communications
- Challenges with ROV technology, “work-class” ROVs used by industry may not be necessary, cheaper instruments may be sufficient to meet the scientific community’s needs; smaller ROV would require a smaller ship, possibly smaller crew
- Smaller ROVs on more ships would make the technology more accessible (transformative)
- Power, potential for leveraging marine renewable energy
- High cost of ROV operation is people

6.3.2. Communications - optical wireless communication is relatively limited in distance (<100m) but data rates are extremely high (Mbits/sec), which is a game changer. Meanwhile, significant advancements in acoustic communications has been made in recent years, but issues of trust (particularly with regards to reliability) and understanding of the technology persist.

- Systems are falling back to acoustics because depths are >100 m and ROV/AUVs are not always an option; current systems generally use buoys or ships at the surface
- The technology to get signal quickly enough for warning systems is a significant challenge; acoustics do have the depth range, but there must be a surface craft/system to relay the data (900 bits/sec in 3000m water)
- Hazards-related communication would be further complicated by noise and interference due to the event itself (earthquake, tsunami, etc.) and subsequent events like submarine landslides
- Redundancy and data relays
- Balloon technology, machine learning: when to make decisions on release
- Distributed acoustic sensing from on-land to offshore; 20 km limit using cheap existing fiber optic cables; redundancy of using a single onshore station to record multiple offshore locations
- Satellite communications make connections anywhere on earth more feasible

6.3.3. Data analysis, Visualization, and Communication
- Process, convert, analyze raw data to extract and present features of interest to scientists, engineers, and early warning of hazards
- Description/guidelines/list of scientific questions would help visualization community understand the needs of the research community
- Helps with hypothesis building; can also be used to compare and validate simulation model results with sensor measurements
- Community outreach; policy making; public perception

6.3.4. Machine learning and prediction
- Analyze data for patterns, trends, recurrence, periodicity, etc.
- Correlate data patterns with events

6.3.5. Telemetry

6.3.6. Data synergies

It is recommended to partner with the Joint Task Force (JTF) investigating submarine telecommunications cables for ocean and climate monitoring and disaster warning (https://www.itu.int/en/ITU-T/climatechange/task-force-sc/Pages/default.aspx).

Additionally, promising areas of investigation were discussed that do not fall perfectly into the general categories listed above. Low-technology methods for hazard detection (e.g., lahar detection via wire), and quantum gravity meters were noted as worthy topics of investigation. Particularly intriguing is the concept of Internet of Underwater Things (IoUT). As conceptualized in Fig. 8, the IoUT could encompass smart rocks, fish tags, AUVs, ASV, transducers, hydrophones, and host of other sensors, in addition to the related communications technologies (Zheng, 2018).

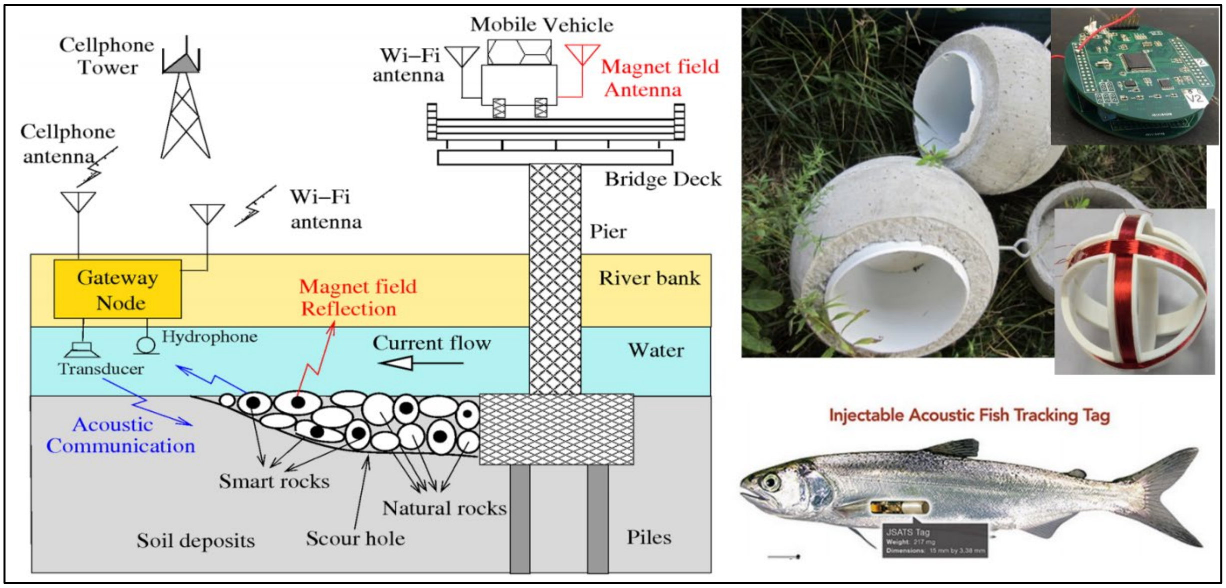

Figure 8: Internet of Underwater Things (IoUT) from workshop presentation of R. Zheng (Zheng, 2018).

7. Managing Environmental Impacts

The workshop participants identified potential environmental impacts caused by seafloor sensors. Table 4 shows the primary environmental impacts.

Table 4: Environmental impacts of seafloor sensors

1. Potential impact to sea life, and in particular, marine mammals and turtles.
    a. Acoustic signals from sensors
    b. Interaction with autonomous or semi-autonomous vehicles
    c. Toxicity of sensor components
    d. Habitat change
2. Carbon footprint necessary to deploy, maintain, and gather seafloor sensors
3. Abandoning the seafloor sensors leads to additional ocean trash

The workshop participants also discussed how to reduce or manage the environmental impacts shown in Table 4. The overall consensus is that the seafloor sensor developers, scientists, and environmental policy and decision makers need to work together, both during and after sensor development, to balance the tradeoffs between pushing science forward and lessening the environmental impact of the necessary seafloor sensors.

In terms of managing the environmental impacts to sea life, most of the workshop participants agreed that strong policies exist to regulate sensor deployment.

The following additional bullets were captured during the brainstorming session:

- Impacts on benthic habitats
- Marine mammals and turtles: important to stay in front of concerns regarding acoustic signals :
    - Leverage existing literature about the frequencies and ranges of concern
    - Opportunity to mitigate the effects of the transmission with more sensitive instruments. Increase signal to noise ratios without increasing transmit signal strength.
    - Permits required for active transmission work; sound verification exercise to establish safe ranges (math alone may not be sufficient)
    - NSF goes through review process for seismic; attempts are being made to deal with regulatory issues for multibeam sonar. Leverage work being done at University of New Hampshire. Similarly, there are other activities that can be leveraged to avoid having to duplicate all of the testing/analysis for each particular system and data collection.
    - Permitting system is arcane and difficult in some cases (e.g., Langseth cannot record multi-beam while transiting)
    - Mitigating environmental groups' concerns goes beyond permitting processes. Additionally, the permitting processes change. Better communication between scientists, engineers and environmental groups is needed.
    - Autonomous or semi-autonomous vehicles vs. protected species observer requirements
    - Some of the acoustic communication devices may have a larger impact than acoustic release; possibly both much lower than sonar?
    - How do we study these impacts? national fisheries develop recommendations that may or may not reflect reliable scientific knowledge
    - Advocating for new technologies could put us in a position of conflict; there needs to be an independent review of the impacts as part of the process, performed by an objective scientific committee
    - Permitting process is already complex and managed by an external group (NMFS)
    - Relationship between environmental impact and cost, both for installed stations and deployment techniques (e.g., ship time)
    - Being able to retrieve systems rather than considering them "disposable" (also environmental and financial cost of retrieval)
    - Is being biodegradable over some given length of time acceptable? Can inoperable sensors become habitat for marine life?
    - Are elements of the system destructive, such as batteries breaking down over time?

- Research question: do inoperable sensors get buried over time by sediment, small flow velocities?
- National/international restrictions on ship discards/trash overboard might inform specific materials
- Drifting data buoys, sonobuoys (airdropped system)
- Defouling agents, copper, toxic metals
- XBTs (copper wire), anchors (steel, iron)
- Release to recover equipment
- On-shore to off-shore cabled array crossing potentially sensitive shallow water habitats - one option is for the deployment to be drilled from the dry side to some depth beyond the most sensitive habitats
- Sites of interest may become polluted with discarded material if revisited multiple times; this will also impact the behavior of the natural system (fauna, etc.)
- Tracking plastic trash for ocean currents: could a map of known debris on the seafloor be useful scientifically?
- It is important to document evidence that particular sensors/measurements are not of concern, particularly with regard to acoustic communications and marine mammals.

8. Visioning - the Future of Seafloor Sensing

An overall consensus from the workshop participants is that to further seafloor sensor capabilities as well as the science derived from seafloor sensor measurements, we will need to build a diverse community encompassing seafloor sensor developers, scientific end-users within academia, private industry, and government, and policy makers, among others. We also think it is important for academic groups to collaborate more openly amongst themselves. Many sensors spend a large portion of their service lives sitting on shelves, so developing new protocols and mechanisms for sharing sensors is one simple, yet powerful example of enhanced collaboration. By exploring options for lowering sensor insurance costs, we can facilitate loaning/sharing of sensors and support a larger number of researchers.

The workshop participants discussed building community through new or enhanced synergies/collaboration between academia, industry, government, and military. Professional societies, including the American Geophysical Union (AGU), the Hydrographic Society of America (THSOA), the Marine Technology Society (MTS), and the Society for Underwater Technology (SUT), may have an important role to play in bringing together these sectors. An essential aspect of partnerships is recognizing that one discipline's noise is another's signal (e.g., physical oceanography and seismology). Another key partnership opportunity involves working with telecommunications companies to instrument their cables. These companies are generally aware of and not opposed to this possibility. However, the seafloor science community needs to demonstrate to these companies that we will not interfere with their operations or use all of their bandwidth. To do so we will need to carefully define our specifications. This is a potential opportunity for a committee comprising engineers and scientists.

We also noted that industrial sensor development, for instance in the oil and gas industry, is often ahead of academic sensor development, because research and development budgets are larger. However, it may be easier for academic groups to deploy sensors, due to the greater regulatory oversight requirements imposed on industry. Therefore, there is a clear synergy between these groups that should be leveraged to push seafloor sensing science forward.

The following additional items were discussed during the brainstorming session:

- Private foundations should also be included; things like smart cables are connected to foundations, industries, commercial organizations, such as Amazon. They may be willing to partner with scientists as long as their commercial interests are not jeopardized.
- Collaboration with military partners; for instance, partnerships with the U.S. Navy on ROV training.
- Collaboration between research-oriented groups (e.g. NSF, academia) and mission-oriented groups (NOAA, USGS, industry) should be encouraged.
- Specialist scientific communities tend to be small, because their specific technologies are difficult to access and/or use by other scientific communities; efforts to broaden the trained user pool for instruments through organized workshops and other activities organized by a seafloor sensor facility is desirable. Provision of technical support is also a potential responsibility for a seafloor sensor facility.
- Ship transit time can be used for some types of training and instrument testing.
- Funding a competition for marine research related to the goal of pushing sensor technology forward is recommended.
- Communication between the various segments of the seafloor sensing and engineering communities continues to need work. As a starting point, we recommend starting a listserv or sharepoint site with the participants from both seafloor sensors workshops.

Conclusion

Recommendations for Actionable Strategies:

While progress on a number of technologies in recent years has been significant, there are general categories of challenges that remain unmet, requiring further research and development. Specific examples include:

- Power harvesting
- Decreased power consumption
- Communications
- Timing
- Interoperability
- Sensor drift and calibration
- Long-duration autonomy
- Modular and reconfigurable sensors/network

It is recognized that work on all of the above will be an ongoing process, due to the feedback system that exists between technology and science questions. As the data improve, more questions arise and become feasible to answer, leading, in turn, to new technological requirements. The discussed sensor needs and technology gaps are formidable, and will require significant research investments led by multi-disciplinary teams from academia, industry, and government working with sensor developers and end-users.

An overarching recommendation is to establish a seafloor sensing consortium or virtual center, dedicated to training, facilitating communication, and collaboration opportunities. This could take the form of an NSF research coordination network (RCN) on seafloor sensing, although other models would also be viable. The envisioned consortium will hold periodic events to bring together diverse stakeholder groups, working across academic, industry, government and military sectors. The consortium will coordinate conferences and workshops and special issues of journals related to seafloor sensing. The consortium will also maintain a database of potentially loanable sensors and assist with associated insurance issues, shipping, and training. Access to a test tank is an important consideration. Another key role of the consortium will be to coordinate work on environmental impacts of sensors, including maintaining standards and documenting existing permits and test results. The consortium may be able to purchase equipment to be used as a pool (shared resource) for researchers from various universities/organizations and to organize in-water demonstrations and training with equipment.

Through implementation of the recommendations in this report and enhanced collaboration between the scientific and engineering communities engaged in seafloor sensing, we anticipate rapid progress on the remaining challenges within the next decade and beyond.

Acknowledgments

The workshop was funded by the National Science Foundation (NSF), OCE Division of Ocean Sciences (Award # 1817257). The support is gratefully acknowledged. We would like to specifically thank Kandace Binkley, Deborah Smith, John Bikoba, Shubra Gangopadhyay, and Maurice Tivey from NSF for their participation and support of the workshop as well as all workshop participants. We appreciate the support of the graduate student volunteers: Chase Simpson, Nick Forfinsky-Sarkozi, Jason Sarkozi-Forfinsky, and Yingqing Qiu. Finally, we would like to thank Annie Ingersoll for providing significant workshop support.

References:

Ahmed, N., and Y.R. Zheng, Design and Evaluation of Low-Cost and An Energy Efficient Magneto Inductive Sensor Node for Wireless Sensor Networks, *IEEE Systems Journal*, DOI: 10.1109/JSYST.2018.2841872, in press June 2018.

Bachmayer, R., Leonard, N., Graver, J., Fiorelli, E., Bhatta, P., and Paley, D., "Underwater gliders: recent developments and future applications," in *Proc. International Symposium on Underwater Technology* (UT), Apr. 2004, pp. 195–200.

Barnes, C.R., Best, M.M.R. and Zielinski, A. The NEPTUNE Canada regional cabled ocean observatory. Technology (Crayford, England), Vol. 50, No. 3, 2008.

Chen, C.F., Chan, H.C., Chang, R.I., Tang, T.Y., Jan, S., Wang, C.C., Wei, R.C., Yang, Y.J., Chou, L.S., Shin, T.C. and Kuo, K.W. Data demonstrations on physical oceanography and underwater acoustics from the MArine Cable Hosted Observatory (MACHO). In OCEANS, 2012-Yeosu, pp. 1-6. IEEE, 2012.

Chen, G., K. Mischaikow, R.S. Laramee, P. Pilarczyk, and E. Zhang, Vector Field Editing and Periodic Orbit Extraction Using Morse Decomposition, *IEEE Transactions on Visualization and Computer Graphics*, Vol 13(4), 2007, pp 769-785.

Favali, P., Person, R., Barnes, C.R., Kaneda, Y., Delaney, J.R. and Hsu, S.K. Seafloor observatory science. Proceedings of the OceanObs, 9, pp. 21-25, 2010.

Favali, P., Chierici, F., Marinaro, G., Giovanetti, G., Azzarone, A., Beranzoli, L., De Santis, A., Embriaco, D., Monna, S., Bue, N.L. and Sgroi, T. NEMO-SN1 abyssal cabled observatory in the Western Ionian Sea. IEEE Journal of Oceanic Engineering, Vol. 38, No. 2, pp.358-374, 2013.

Gomes, K., Cline, D., Edgington, D., Godin, M., Maughan, T., McCann, M., O'Reilly, T., Bahr, F., Chavez, F., Messie, M., Das, J., Rajan, K., "ODSS: A Decision Support System for Ocean Exploration," *Proc. 29th IEEE International Conference on Data Engineering Workshop on Data-Driven Decision Guidance and Support Systems* (DGSS), 2013.

Hsiao, N.C., Lin, T.W., Hsu, S.K., Kuo, K.W., Shin, T.C. and Leu, P.L. Improvement of earthquake locations with the Marine Cable Hosted Observatory (MACHO) offshore NE Taiwan. Marine Geophysical Research, Vol. 35, No. 3, pp.327-336, 2014.

Kaushal H., and G. Kaddoum, Underwater Optical Wireless Communication, *IEEE Access*, pp. 1518 – 1547, April 2016.

Kawaguchi, K., Kaneda, Y. and Araki, E. The DONET: A real-time seafloor research infrastructure for the precise earthquake and tsunami monitoring. In Proceedings of IEEE/MTS OCEANS 2008- Kobe Techno-Ocean, pp. 1-4, 2008.

Kelley, D.S., Delaney, J.R. and Juniper, S.K. Establishing a new era of submarine volcanic observatories: Cabling Axial Seamount and the Endeavour Segment of the Juan de Fuca Ridge. Marine Geology, 352, pp.426-450, 2014.

Lawrance, N., DeBortoli, R., Jones, D., McCammon, S., Milliken, L., Nicolai, A., Somers, T., and Hollinger, G., "Shared autonomy for low-cost underwater vehicles," *Journal of Field Robotics*, 2018, to appear.

Li, J., Kaess, M., Eustice, R.M., and Johnson-Roberson, M., "Pose-graph SLAM using Forward-looking Sonar," *IEEE Robotics and Automation Letters*, vol. 3, no. 3, July 2018, pp. 2330-2337.

Middlemiss, R. P., Bramsiepe, S. G., Douglas, R., Hough, J., Paul, D. J., Rowan, S., & Hammond, G. D. (2017). Field Tests of a Portable MEMS Gravimeter. Sensors (Basel, Switzerland), 17(11), 2571. http://doi.org/10.3390/s17112571.

Mora, A., Ho, C., and Saripalli, S., "Analysis of adaptive sampling techniques for underwater vehicles," *Autonomous Robots*, vol. 35, no. 2-3, pp. 111–122, Oct. 2013.

Palacios, J., H. Yeh, W. Wang, Y. Zhang, R.S. Laramee, R. Sharma, T. Schultz, and E. Zhang, Feature Surfaces in Symmetric Tensor Fields Based on Eigenvalue Manifold, *IEEE Transactions on Visualization and Computer Graphics*, Vol 22(3), 2016, pp. 1248-1260.

Petres, C., Pailhas, Y., Patron, P., Petillot, Y., Evans, J., and Lane, D., "Path planning for autonomous underwater vehicles," *IEEE Transactions on Robotics*, vol. 23, no. 2, pp. 331–341, Apr. 2007.

Puillat, I., Person, R., Leveque, C., Drogou, J.F., Diepenbroek, M., Garreau, P., Waldmann, C. and Auffret, Y. Standardization prospective in ESONET NoE and a possible implementation on the ANTARES Site. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 602(1), pp. 240-245, 2009.

Rypkema, N.R, Fischell, E.M., Schmidt, H., "One-Way Travel-Time Inverted Ultra-Short Baseline Localization for Low-Cost Autonomous Underwater Vehicles" *Proc. IEEE International Conference on Robotics and Automation* (ICRA), 2017

Singer, A., J. Nelson, and S. Kozat, Signal Processing for Underwater Acoustic Communications, *IEEE Commun. Mag*., Vol. 47, No. 1, Jan. 2009, pp. 90–96.

Strom, B., Brunton, S. L., & Polagye, B., Advanced control methods for cross-flow turbines. *International Marine Energy Journal*, Vol. 1, No. 2, pp. 129-138, Nov. 2018

Sun, Z., and and I.F. Akyildiz, Key Communication Techniques for Underground Sensor Networks, in *Foundations and Trends in Networking* series, Nowpublishers.com, 2012.

Taylor, S.M. Transformative ocean science through the VENUS and NEPTUNE Canada ocean observing systems. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 602(1), pp.63-67, 2009.

Wilcock, W., P. Bodin, J. Delaney, J. Vidale, (editors), Workshop report: Seafloor geodesy in Cascadia, June 11-12, 2012. available at http://faculty.washington.edu/wilcock/wordpress/wp-content/uploads/2014/10/SeafloorGeodesyCascadiaReport_ver130203_HighRes.pdf.

Woods Hole Oceanographic Institute (WHOI) Press, Optical system promises to revolutionize undersea communications, Feb. 2010, [online] available, http://www.whoi.edu/mr/pr/viewArticle.do?id=69687

Zhang, E., H. Yeh, Z. Lin, and R.S. Laramee, Asymmetric Tensor Analysis for Flow Visualization, *IEEE Transactions on Visualization and Computer Graphics*, Vol. 15(1), 2009, pp. 106-122.

Zheng, Y.R., J. Wu, and C. Xiao, Turbo Equalization for Underwater Acoustic Communications, *IEEE Commun. Mag.*, Vol. 53, No. 11, pp. 79-87, Nov. 2015.

Appendix A: Workshop Agenda

NSF-Sponsored Seafloor Sensors/Instrumentation Workshop

Gleneden Beach, Oregon, July 12-13

Agenda

Objectives: The overarching workshop goal is to chart the future for instrumenting the seafloor to provide real-time data. A key focus will be to develop strategies to enable early warning of geohazards. Topics to be explored include the development of sensors to measure seafloor deformation, temperature and fluid flow with high resolution over broad areas, strategies for transmitting the data to land quickly and efficiently, and methods for obtaining energy from the environment.

Day 1: Thursday, July 12

8:00 – 8:45	Seating and coffee, light breakfast
8:45 – 9:00	Welcome and workshop objectives Chris Parrish, Oregon State University
9:00 – 9:15	NSF vision and anticipated outcomes Shubhra Gangopadhyay and Maurice Tivey, National Science Foundation
Session I: Understanding science needs for seafloor sensing Focus on the following questions: 1) What types of data do we need? 2) Why do we need those data? 3) What are future directions for the collection and use of the data?	
9:15 – 10:15	Talks 1-5 (12 min each): David Schmidt, Spahr Webb, Heidrun Kopp, Diego Melgar, Katrin Hafner (Moderator: Trehu)
10:15 – 10:30	Panel discussion for Talks 1-5
10:30 – 10:45	Coffee break
10:45 – 11:45	Talks 6-10 (12 min each): Nathan Miller, Brendan Philip, Ben Mason, Aaron Gallant, Kim Swords (Moderator: Mason)
11:45 – 12:00	Panel discussion for talks 6-10
12:00 – 13:00	Lunch (catered)
Session II: Understanding current state-of-the-art in seafloor sensing (including power, communication, on-board processing, etc.)	
13:00 – 14:00	Talks 1-5 (12 min each): Geoff Hollinger, Alex Pang, John Selker, Mike Harrington, Clare Reimers (Moderator: Hollinger)

14:00 – 14:15	Panel discussion for talks 1-5
14:15 – 14:30	Break
14:30 – 15:30	Talks 6-9 (12 min each): Aaron Marburg, Eugene Zhang, Mark Zumberge, William Wilcock (Moderator: Selker)
15:30 – 15:45	Panel discussion for talks 6-9
Session III: Brainstorming kick-start	
15:45 – 17:00	Overview of goals for Day 2. Capture high-level themes/topics from Day 1 that will inform the Day 2 brainstorming sessions (no discussion—just capture key points) (Moderator: Parrish)
18:00	Dinner at Side Door Café

Day 2: Friday, July 13

8:00 – 8:45	Seating and coffee, light breakfast
8:45 – 9:00	Recap of Day 1: review of items from Brainstorming Kick-Start
Session IV: Lightning talks	
9:00 – 9:30	Lightning talks (0-2 slides) (Moderator: Parrish)
Session V: Gap analysis: where are the chasms between seafloor data needs and what the current state-of-the-art technologies can deliver?	
9:30 –10:45	Small group break outs 1
10:45-11:00	Coffee break
11:00 – 12:30	Small group break outs 2
12:30 – 13:30	Lunch (catered)
Session VI: Visioning: how do we close these gaps and design, build, implement and operate the seafloor sensors/networks of the future?	
13:30 – 14:30	Report-outs from small groups
14:30 – 14:45	Break
14:45 – 16:00	Full-group visioning. Need to capture big-ticket items to address in reports. Ensure that we are tying back to overarching workshop goals and objectives. Draft report outline.
16:00	Workshop close. Shuttles depart for PDX. (Note: there will also be a shuttle to PDX on the morning of July 14th, but anyone with an early morning flight may want to return on the evening of the 13th.)

Next 2 months	Synthesis, report writing

Appendix B: Attendees

First Name	Last Name	Institution, organization, or affiliation(s):
Rob	Cavagnaro	Applied Physics Laboratory, UW (PMEC)
Jnaneshwar	Das	Arizona State University
Xiong	Yu	Case Western Reserve University
Timothy	Melbourne	Central Washington University
Nate	Lindsey	Earth & Planetary Science, Berkeley
Heidrun	Kopp	GEOMAR Helmholtz Centre for Ocean Research
Sheng	Dai	Georgia Institute of Technology
Andrew	Newman	Georgia Institute of Technology
Neville	Palmer	GNS Science, New Zealand
Laura	Wallace	GNS Science; University of Texas Institute for Geophysics
Bob	Woodward	Incorporated Research Institutions for Seismology
Katrin	Hafner	Incorporated Research Institutions for Seismology
Samer	Naif	Lamont-Doherty Earth Observatory
James	Gaherty	Lamont-Doherty Earth Observatory
Spahr	Webb	Lamont-Doherty Earth Observatory
Charlotte	Rowe	Los Alamos National Laboratory
Navid	Jafari	Louisiana State University
Y. Rosa	Zheng	Missouri University of Science and Technology
John	Bikoba	National Science Foundation
Shubhra	Gangopadhyay	National Science Foundation
Maurice	Tivey	National Science Foundation
Erica	Fruh	NOAA Fisheries
Jeff	Anderson	NOAA Northwest Fisheries Science Center
Martin	Heesemann	Ocean Networks Canada, University of Victoria
Zhanping	Liu	Old Dominion University
Geoffrey	Hollinger	Oregon State University
Ben	Mason	Oregon State University
Michael	Olsen	Oregon State University
Christopher	Parrish	Oregon State University
Yingqing	Qiu	Oregon State University
Nicholas	Tufillaro	Oregon State University
Eugene	Zhang	Oregon State University
Nick	Forfinski-Sarkozi	Oregon State University
John	Nabelek	Oregon State University
Clare	Reimers	Oregon State University
Jason	Sarkozi-Forfinski	Oregon State University
Anne	Trehu	Oregon State University
John	Selker	OSU, CTEMPS, TAHMO

Jerry	Paros	Paroscientific, Inc.
Chris	Kontoes	RBR
Jonathan	Berger	Scripps Institution of Oceanography
Mark	Zumberge	Scripps Institution of Oceanography
Thomas	Coleman	Silixa LLC
Taylor	Martin	Silixa LLC
Kim	Swords	Sonardyne Inc.
Glenn	Sasagawa	UC San Diego
Matthew	Cook	UC San Diego, Scripps Institution of Oceanography
Aydin	Babakhani	UCLA
Alex	Pang	University of California, Santa Cruz
Guifang	Li	University of Central Florida
Zhuoyuan	Song	University of Florida
Scott	Wasman	University of Florida
Aaron	Gallant	University of Maine
Diego	Melgar	University of Oregon
Tyler	Newton	University of Oregon
Amy	Williamson	University of Oregon
Jie	Huang	University of Texas at San Antonio
Brendan	Philip	University of Washington
David	Schmidt	University of Washington
William	Wilcock	University of Washington
Aaron	Marburg	University of Washington Applied Physics Laboratory
Keshab	Gangopadhyay	University of Missouri
Robert	Wyland	US Geological Survey, Marine Facility
Nathan	Miller	USGS
Michael	Harrington	UW/APL

Appendix C: Workshop Presentations

Note: all workshop permissions for which permission was received from the author(s) are being made available on the workshop website.

Invited Presentations:

Harrington, M., 2018. Ocean Observatories Initiative: Cabled Array Observatory. Seafloor Sensors Workshop (this workshop), 12 July, Gleneden Beach, Oregon.

Hafner, K., 2018. Global Seismology Science Needs for Long-Term High Quality Seafloor Seismographs. Seafloor Sensors Workshop (this workshop), 12 July, Gleneden Beach, Oregon.

Hatchell, P., R. de Vries, V. Gee, H. Cousson, J. Lopez, K. Swords, S. Dunn, N. Street, A. Parsons, J. Cheramie, and E. Fischer, 2018. Seafloor Deformation Monitoring: Past, Present, Future. Seafloor Sensors Workshop (this workshop), 12 July, Gleneden Beach, Oregon.

Hollinger, G., 2018. Autonomous Decision Making in Seafloor Sensing: The role of AUV systems. Seafloor Sensors Workshop (this workshop), 12 July, Gleneden Beach, Oregon.

Kopp, H., D. Lange, M. Urlaub, F. Petersen, and K. Hannemann, 2018. The GeoSEA Array: in-situ monitoring of seafloor deformation. Seafloor Sensors Workshop (this workshop), 12 July, Gleneden Beach, Oregon.

Marburg, A., 2018. Residency, Autonomy, and Perception (and what it might have to do with ocean instrumentation). Seafloor Sensors Workshop (this workshop), 12 July, Gleneden Beach, Oregon.

Mason, B., and A. Gallant, 2018. Seafloor Sensors and Geotechnical Engineering. Seafloor Sensors Workshop (this workshop), 12 July, Gleneden Beach, Oregon.

Melgar, D., 2018. The role of offshore observations in earthquake and tsunami early warning. Seafloor Sensors Workshop (this workshop), 12 July, Gleneden Beach, Oregon.

Miller, N., and J. Collins, 2018. Design priorities for a rapid-response seafloor seismograph capability. Seafloor Sensors Workshop (this workshop), 12 July, Gleneden Beach, Oregon.

Philip, B., and E. Solomon, 2018. Monitoring fluid sources, transport and *in situ* pore pressures within Subduction Zones. Seafloor Sensors Workshop (this workshop), 12 July, Gleneden Beach, Oregon.

Reimers, C., 2018. Seafloor sensors powered by benthic microbial fuel cells relaying data acoustically. Seafloor Sensors Workshop (this workshop), 12 July, Gleneden Beach, Oregon.

Schmidt, D., 2018. The Scientific Need for Seafloor Geodesy. Seafloor Sensors Workshop (this workshop), 12 July, Gleneden Beach, Oregon.

Selker, J., 2018. Fiber optics and other emerging technologies in seafloor sensing. Seafloor Sensors Workshop (this workshop), 12 July, Gleneden Beach, Oregon.

Webb, S., L. Wallace, D. Chadwell, N. Palmer, Y. Ito, K. Mochizuki, D. Saffer, E. Solomon, and P. Fulton, 2018. Monitoring contemporary deformation and seismicity at the offshore Hikurangi subduction margin. Seafloor Sensors Workshop (this workshop), 12 July, Gleneden Beach, Oregon.

Wilcock, W., 2018. Real-time Offshore Geophysical Monitoring of the Cascadia Subduction Zone: Applications to Earthquake and Tsunami Early Warning. Seafloor Sensors Workshop (this workshop), 12 July, Gleneden Beach, Oregon.

Zhang, E., 2018. Tensor Fields in Seafloor Data and Their Visualization. Seafloor Sensors Workshop (this workshop), 12 July, Gleneden Beach, Oregon.

Lightning Session Presentations:

Cavagnaro, R., and J. Joslin, 2018. Powering an Autonomous Instrumentation Platform with Wave Energy. Seafloor Sensors Workshop (this workshop), 13 July, Gleneden Beach, Oregon.

Das, J., 2018. Data-driven Robotic Sampling for Marine Ecosystem Monitoring. Seafloor Sensors Workshop (this workshop), 13 July, Gleneden Beach, Oregon.

Dai, S., 2018. Geotechnical Testing for Hydrate-Bearing Sediments. Seafloor Sensors Workshop (this workshop), 13 July, Gleneden Beach, Oregon.

Gaherty, J., 2018. PacificArray: A grassroots international collaboration. Seafloor Sensors Workshop (this workshop), 13 July, Gleneden Beach, Oregon.

Jafari, N., S. Bentley, K. Xu, J. Georgiou, J. Maloney, M. Miner, J. Obelcz, and J. Chaytor, 2018. Mass Wasting Processes and Products of the Mississippi Delta Front: Data Synthesis and Observation. Seafloor Sensors Workshop (this workshop), 13 July, Gleneden Beach, Oregon.

Kontoes, C., 2018. RBRconcerto3 APT Early Earthquake and Tsunami Logger. Seafloor Sensors Workshop (this workshop), 13 July, Gleneden Beach, Oregon.

Lindsey, N., C. Dawe, and J. Ajo-Franklin, 2018. Distributed Acoustic Sensing on the Seafloor:

an example from offshore Northern California. Seafloor Sensors Workshop (this workshop), 13 July, Gleneden Beach, Oregon.

Naif, S., 2018. Seafloor electromagnetic instrumentation. Seafloor Sensors Workshop (this workshop), 13 July, Gleneden Beach, Oregon.

Pang, A., 2018. Remote Sensing of Rip Currents. Seafloor Sensors Workshop (this workshop), 13 July, Gleneden Beach, Oregon.

Parros, J., 2018. Seismic + Oceanic Sensors. Seafloor Sensors Workshop (this workshop), 13 July, Gleneden Beach, Oregon.

Rowe, C., 2018. Improving geophysical (seismic) models and methods with ocean-floor instrumentation. Seafloor Sensors Workshop (this workshop), 13 July, Gleneden Beach, Oregon.

Williamson, A., and A.V. Newman, 2018. Geodetic Resolution of the Megathrust. Seafloor Sensors Workshop (this workshop), 13 July, Gleneden Beach, Oregon.

Woodward, B., A. Frassetto, and K. Aderhold, 2018. Insights from Operations of the U.S. Ocean Bottom Seismograph Instrument Pool. Seafloor Sensors Workshop (this workshop), 13 July, Gleneden Beach, Oregon.

Zheng, Y.R., 2018. Underwater Wireless Communications: Overview and Recent Progress. Seafloor Sensors Workshop (this workshop), 13 July, Gleneden Beach, Oregon.

Zumberge, M., 2018. An optical Fiber Strainmeter. Seafloor Sensors Workshop (this workshop), 13 July, Gleneden Beach, Oregon.