Report on NSF-Sponsored Workshop BLUE-UCI2021

Advancing Underwater Cyber Infrastructure for Blue Science

Workshop dates: Jan. 12 and Jan 14, 2021

Report date: Feb. 8, 2021

Executive Summary

The NSF–sponsored workshop on Advancing Underwater Cyber Infrastructure for Blue Science, or BLUE-UCI 2021, was held virtually on Jan. 12 and Jan. 14, 2021. Webinar presentations were organized into four sessions: 1. Ocean Science Perspectives: Needs and Challenges; 2. IoUT Hardware, Electronics, and Applications in Extreme Environments; 3. Underwater Communications, Signal Processing, and Networking; and 4. Marine Robotics and Artificial Intelligence for IoUT.

Zoom discussion panels followed the webinar sessions and discussed three important topics related to underwater cyber infrastructure: Q1. What are the most important challenges in underwater cyber infrastructure? Q2. What are the actions we can take to address these challenges in short term (~5 years) and in long term (~10 years)? Q3. What are the environmental and societal impacts of the technological advances in underwater cyber infrastructure?

Based on the webinar presentations and panel discussions, the organizing team summarized four recommendations and several specific research directions. Those will help the NSF with a strategic planning and funding program that supports the next-generation advances in underwater technologies while reducing environmental footprint. As the UN Decade of Ocean Science for Sustainable Development starts in 2021, it is timely for the NSF to develop such a program that addresses the cyber infrastructure of underwater technologies and directly impacts the blue economy and the blue science.

The details of the workshop, including this report and the video recordings of the presentations, are found on the workshop website: https://www.blue-uci2021.org

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1. Workshop Overview

The NSF–sponsored workshop on Advancing Underwater Cyber Infrastructure for Blue Science, or BLUE-UCI 2021, was held virtually on Jan. 12 and Jan. 14, 2021. The overall goal of the workshop was to help NSF with strategic planning in addressing the cyber infrastructure of underwater technologies affecting the blue economy, in particular an appropriate funding program that supports the next-generation advances in underwater technologies while reducing environmental footprint. The workshop was divided into four sessions:

- Session 1 - Ocean Science Perspectives: Needs and Challenges
- Session 2 - IoUT Hardware, Electronics, and Applications in Extreme Environments
- Session 3 - Underwater Communications, Signal Processing, and Networking
- Session 4 - Marine Robotics and Artificial Intelligence for IoUT

Each session consisted of webinar presentations and a discussion panel. The webinar presentations included one 30-minute keynote speech, two to four 10-minute short talks, and several 3-minute pre-recorded lightning talks. The discussion panel ran for an hour after the webinar presentations. The discussion panel utilized a Zoom meeting and four breakout rooms to facilitate the discussion. The workshop schedule and the list of presentations are detailed in Appendix A. Links to the video recordings of the presentations are also included on the workshop website: https://www.blue-uci2021.org/agenda.html.

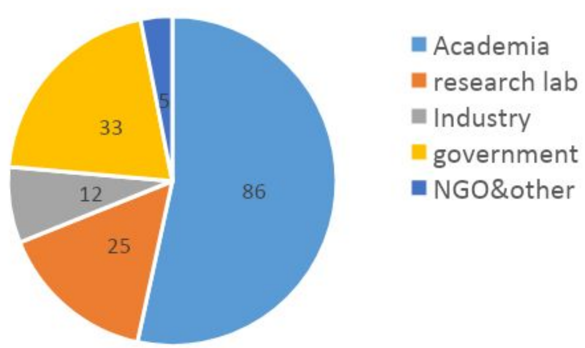


Fig. 1. Attendee Organizations

The total number of registrants for the workshop webinar is 161, among those, 53.4% are from academia, 23.0% are from research laboratories and industry, 20.5% are from the government, and 3.1% are from non-profit organizations or other organizations, as shown in Fig. 1. Based on the emails of the registrants, 84.5% of the registrants are US-based, and 15.5% are international participants.

The actual attendance to each session is listed in Table 1, based on the Zoom webinar attendance report and the time durations of the attendees. Attendees who stayed in a session for less than 10 minutes are excluded from the counts.

Table 1. Workshop attendance

Session #	Session 1	Session 2	Session 3	Session 4
Webinar	99	98	84	70
Discussion panel	52	56	63	50

2. Panel Discussions

The panel discussions were centered on the following three questions:

Q1. What are the most important challenges in underwater cyber infrastructure?
Q2. What are the actions we can take to address these challenges in short term (~5 years) and in long term (~10 years)?
Q3. What are the environmental and societal impacts of the technological advances in underwater cyber infrastructure?

Q1. Most important challenges

The panels recognize the importance for an underwater cyber infrastructure to include or provide the following functionalities:

- Underwater Positioning, Navigation, and Timing (PNT) systems that can provide services similar to the Global Positioning System (GPS);
- Wired and wireless communication networks for the transmission and sharing of data among all assets;
- Power/ energy supplies to support underwater and marine systems;
- Sensors and actuators that form the internet of underwater things (IoUT) systems;
- Robotic platforms such as Remotely Operated Vehicles (ROV), Autonomous Underwater Vehicles (AUV), gliders, and other marine robots for data collection and infrastructure maintenance.

Underwater PNT or GPS systems and communication networks are essential to providing connectivity between underwater assets and human activities. Localization and communication are tightly coupled and serve as the core of the cyber infrastructure. Underwater communication networks connect the PNT system nodes, mobile platforms, and underwater platforms, while underwater PNT provides critical timing to communication networks and critical positioning and navigation information to underwater assets. The recommendation from OceanObs2019 clearly suggested "a sustained multipurpose acoustic network for passive monitoring, tomography, underwater positioning and communication in the integrated Arctic observing system, with eventual transition to global coverage." Such a unified cyber infrastructure is also critical to other research areas, technology development, and the blue economy.

On the other hand, no system can operate without a reliable power supply, and communications, mobility, and sensing come at a significant energetic cost, and typically represent the largest portion of system energy budgets. Despite recent advancements in energy technologies, providing efficient power or energy to underwater infrastructures remains a significantly challenging problem that is interrelated with the push for innovation in other areas of cyber infrastructure.

If a cyber infrastructure can provide the PNT, communication, and power services, underwater mobile platforms and sensors/actuators can take advantage of it and provide enhanced services to all applications. Although existing sensor/actuator technologies may be modified to suit some underwater needs, unique challenges associated with underwater sensing and actuation have not been sufficiently addressed, including high pressure of deep-ocean, long-term deployment, large scale and spatial coverage, extreme heat/corrosion conditions, biofouling, special sensitivity requirements related to microplastics, biomaterial, bacteria sensing. Integration of sensors into robotic platforms furthers demand for sensor miniaturization and power management. In addition to those challenges, marine robotic platforms need to operate autonomously with high precision and reliability. These demands require a high level of intelligence to deal with faults and unexpected environmental changes over a long operation period.

The priorities and technical challenges of these systems are tightly related to the targeted applications. For example, the commercial sector includes fisheries, shipping, oil and gas, and underwater mining; the scientific research sector includes environmental sensing and monitoring, maritime archaeology, marine biology, and physical, geological, biological, and chemical oceanography. In the fishery and shipping applications, underwater GPS and tracking could enable asset tracking and fisheries technologies with less bycatch and ecosystem damage; underwater wireless communications and sensing technologies can improve interoperability to reduce cost; utilizing small AUVs and marine robots can also improve remote operations and reduce cost. In the underwater mining applications, durable and robust underwater ROVs and robots are highly desirable to reduce risk of human operators in extreme conditions; underwater sensing, communications and tracking are essential for robotic platforms to perform intelligent operations. In the environmental studies and oceanography applications, it is challenging to provide any of the services for long-term deployment and large-scale operation. In particular, it is desirable to have the PNT service at the basin scale without strong noise pollution; the high-bandwidth large-range communication networks will enable AUVs and marine robots to sample areas of interests in real-time; sensing technologies are needed for detecting and tracking microplastics, CO_2, and pH and other ocean variables that have been elusive to measure without physical ocean samples. In marine biology studies, softbody sensors and robots are desirable in some applications and deep-ocean in situ sensing is also desirable.

As for those underwater scientific fields and applications, the panels have also identified some potential enabling technologies and research challenges. The potential enabling technologies include but not limited to underwater IoT, underwater communications and networking, underwater GPS/tracking, underwater robotic design and control, marine power energy supply, and underwater sensors and actuators. The research challenges include but not limited to: How to conduct long-term deep ocean in situ sensing? How to conduct long-term large-scale microplastics sensing? How to deploy long-term underwater environmental sensing? How to detect the underwater pollutants (e.g., chemicals, particles, industrial, agricultural, and residential waste, noise, or the spread of invasive organisms) and effectively deliver the sensed information? How to balance the underwater sensors' durability and robustness? How to reduce the power demand of underwater mining? How to guarantee the robustness of underwater mining operations in extreme underwater conditions? How to reduce the power demand of underwater mining? How to establish interoperability to reduce the underwater research cost?

In terms of performance metrics, different application areas also exhibit different priorities in terms of reliability, cost, maintenance, interoperability, and security. Significant obstacles are present in the existing underwater technologies. For example, the reliability of energy sources, positioning systems, communication networks, and sensing instruments is of critical importance, especially for the long-term operation of sensing platforms. Cost and maintenance are very sensitive to the fishery and shipping sector. Interoperability is important for scaling up the operations in underwater mining and sensing, as well as promoting collaboration and competition. System security is of high importance for military applications and may adopt similar approaches used by terrestrial systems for commercial applications and scientific research.

As technologies in communication, sensing, and autonomy have enabled the oceanography community to push forward the concept of a networked ocean (as envisioned through the UN Decade of the Ocean that began in 2021), the strategic focus on underwater cyber infrastructure is timely. The panels recognized the differences in mission, vision, and resource management taken by NSF and DoD agencies (ONR, NASA, DARPA, etc.). Some programs often identify a single, most compelling application or challenge that requires multiple, simultaneous technology advances to achieve. Such examples include the GPS project from the Navy, the moon-landing and Mars exploration projects from NASA, the desert and urban autonomous driving challenges from DARPA, as well as the global ocean drifter ARGO program from NOAA. In contrast, NSF's approach to infrastructure often identifies the most important needs common to many application areas and builds infrastructure to serve those needs. For example, the NSF UNOLS academic research fleet program provides ship time to support all areas of ocean science and engineering research. The NSF Ocean Observatory Initiative (OOI) program and many other NSF's large facilities are listed here.

Several panelists working at the interface of ocean science and engineering reported that they have had difficulty obtaining NSF funding to support and test cyber infrastructure-related developments. Funding available from NSF-OCE primarily supports basic research, and science-driven experiments may not have the flexibility required for sufficient design, testing, or development of higher-risk technological development. Similarly, funding driven by engineering needs would benefit from opportunities to field-test and harden new technologies in realistic environments, working within a research team focused on high impact, contemporary issues in ocean science. NSF investment in underwater cyber infrastructure could potentially be transformative to simultaneously enable research advances typically supported by different programs or directorates.

The dialogue between ocean scientists and engineering researchers revealed significant gaps between ocean science and underwater engineering. On the one hand, ocean scientists see a lot of needs in better engineering solutions, ranging from energy harvesting, PNT, wireless communications, and sensing instrumentation. On the other hand, engineering researchers don't see what applications their research and innovations might target, and many do their research because of their curiosity or "boredom". The gap between engineering research and fieldable instrumentation that serves ocean scientists is often so big that many engineering innovations fall into the "valley of death". The relatively small size of the scientific oceanography community does not provide sufficient profit or market incentive for manufacturers. Some panelists commended the NSF I-CORPS program as a great mechanism of engaging academic researchers with industry and market and the NSF PFI (Partnership for Innovation) program and the Technology Transfer (TT) options in other programs for their effort on bridging the gap.

Many panelists also recognized that the UN Decade of Blue Science Initiative starts in January 2021, and emphasized that it is desirable to identify a breathtaking goal in underwater applications. Examples mentioned by some panelists include an organized large scale effort to understand the spatial variability of the effects of climate change, mapping 90% of the global ocean, any-time any-where connectivity in the ocean, revolutionizing the fishery industry, connecting oceans with all people, underwater video transmission, underwater internet, cleaning the global ocean, deep ocean tourism, and ocean habitats. The panels would recommend identifying a commonly needed infrastructure that can serve multiple applications.

Q2. Short-term and long-term actions

In the panel discussions, we define the short term as 3 -- 5 years and the long-term as 5 -- 10 years. The panels recognized that the advances in underwater technologies often take much longer to achieve than terrestrial technologies and often require much more investment as most underwater technologies face more challenges and obstacles. Some of the biggest obstacles are lack of investment, lots of barriers to entry, lack of economic drivers outside of a small science-driven community, and lack of collaboration.

The panels provided many good suggestions on attainable action items. Those include:

- Enhancing government regulation vs promoting customer-base market and research consortia;
- Incentivizing new products and technology innovations via investment in commercialization such as I-CORPS and SBIR.
- Operating existing technologies in new ways vs developing new technologies -- supporting whichever will enable paradigm changes
- NSF has traditionally favored performance improvement over cost reduction. However, cost reduction would promote scaling up, so cost reduction enables scalability;
- Standardization will improve interoperability, but standardization effort is largely unfunded. Most existing underwater technologies are proprietary systems that may be easier to achieve network/asset security, but really drives the price high and sets high barriers to newcomers;
- Finding common goals to attract a diverse community to work on a grand challenge, dreaming big and deep and far;
- Enabling interaction among engineering and ocean science communities, fostering interdisciplinary collaborations;
- Fostering international collaboration and re-evaluating export control policies and

regulations;
- Stimulating interests in general public and recruiting the next generation of researchers; Creating more media coverage such as movies and broadcasts (My Octopus Teacher, Robert Ballard Ted Talk, etc.), making media splashes such as the national broadcast of NASA spacecraft docking;
- Articulating positive images and societal impacts of ocean technologies to the general public, taking advantage of the UN Decade of Blue Science for Sustainable Development program.

Technologically, the panels discussed specific approaches to addressing some of the cyber infrastructure needs: comparing quantum-based underwater navigation and beacon-based underwater navigation; considering hybrid communication systems that combine cabled systems with wireless systems; Considering a joint network that can provide multiple services such as PNT, communications, and data collection; promoting smart energy harvesting; developing a fleet of cost-effective mobile platforms; exploring new sensing and actuation technology towards large scale deployment. The top three recommended short-term and long-term actions are listed in Table 2.

Table 2. Recommended Actions for the Research Community	
Short-term Actions	**Long-term Actions**
Encourage collaboration between engineering and ocean science communities through workshops, data sharing, and interdisciplinary meetings so that the engineering community becomes more familiar with fundamental questions in oceanography, and the oceanography community becomes aware of the logistical/infrastructure challenges that can be solved through engineering efforts.	Foster inter-agency collaboration and international collaborations; join the UN Decade of Blue Science program; create fundamentally interdisciplinary programs to bridge the funding gap between ocean science and engineering;
Develop shared testbeds, data repositories, and marine assets for underwater research, teaching, and technology development, lower the barrier of entry.	Identify grand challenges for underwater cyber infrastructure: energy, navigation, communications, marine transportation, robotics, and sensing.
Develop training platforms and curricula for underwater technologies including navigation, communications, robotics, and sensing;	Promote interoperability and standardization, address export control and other restrictions

Q3. Environmental and Societal Impacts

The panels identified several environmental impacts that underwater technologies may bring:

- Increased level of underwater noise and interference due to beacon-based constant pinging of underwater GPS system at ~ 900 Hz, strong transmission from sonar imaging systems, and potential increase of acoustic transmission from dense acoustic communication networks;
- Sound pollution from these technologies and surface-based industries (e.g., shipping).
- Increase of plastic, both in the form of microplastics and as "scientific litter" on the seafloor and in the water column due to loss of fishery gear, research instruments, AUVs, and other mobile robots. Currently, the estimated loss of assets is at 10% of the operational deployment. The contribution of the research-related pollution is significantly smaller than that of shipping, fisheries, and other non-scientific human activities, the scientific research community carries an additional burden, and must be sensitive to the microplastic pollution problem, proactively developing and using new materials with less harmful impact to the environment it seeks to study.
- Nets, cables, and surface structures cause entanglement to wildlife (and AUVs), and are subject to additional risk at the surface due to vandalism and physical stressors. Reducing the oceanographic and fisheries communities' reliance on surface buoys and subsurface cables and nets would reduce the threat on endangered marine mammals.

The panels also pointed out many positive societal impacts that underwater technology advances would bring:

- Enabling sustainable economic growth in fishery and aquaculture, shipping, mining, and related industries;
- Improving seafloor mapping of the Exclusive Economic Zone (EEZ) and improving the surveillance of coastal regions;
- Enabling understanding of climate change, formation and prediction of extreme weather, life cycles in oceans and lakes, and other topics that are important for the well-being of the earth;
- Enhancing sensing technologies and increasing data collection to better characterize the ocean and marine resources;
- Educating the general public about how important the oceans and fresh-water bodies are to humanity, as well as the UN Convention of the Law of Seas; Projecting positive images of ocean science research, engineering advances, and technology development;
- Communicating direct and indirect impacts of human activities on oceans and other aquatic systems. Refer to the UN Global Programme of Action for the Protection of the Marine Environment from Land-based Activities. Some good examples of indirect impact are: international trade and shipping increase have put tremendous stress on oceans; extensive salt use for de-icing results in salinity increase in freshwater systems; green gas emission puts a high demand on oceans to absorb more CO_2; everyday use of plastics

leads to heavy microplastics pollution in rivers, lakes, and oceans than lost scientific instruments.

3. Recommendations

The planning team reviewed the workshop webinars and panel discussions, and here, summarize the opinions gathered from the workshop and propose some recommendations to the NSF. It is our hope that these recommendations will help NSF to form a meaningful call for broader participation from the research community to promote fundamental research, technology advancement, and field integration in the near future.

Recommendation 1: developing a program to promote innovation in a sustained and integrated cyberinfrastructure that provides multiple services simultaneously, including but not limited to positioning, navigation, and timing (PNT), communication and networking, energy replenishment, and data collection. Without increasing environmental impacts, the ocean community envisions the urgent needs for a unified multi-purpose cyber infrastructure that is sustainable, achieves the highest performance, and best utilizes the existing resources.

Recommendation 2: promoting interdisciplinary research among ocean science and engineering disciplines, engaging multi-sector collaborations among academia, government, non-profit organizations, and industry, and developing across-national collaborative programs.

Recommendation 3: emphasizing research activities that address broader impacts on both societal and environmental aspects; promoting innovations that help us to understand the influence of human activity and economic development on the ocean environment, and requiring specific measures of success on these efforts.

Recommendation 4: engaging NSF's Mid-scale Research Infrastructure program, other funding agencies, and international partnership to develop a coalition of programs; engaging the UN Decade of Ocean Science for Sustainable Development program.

The potential research topics for a sustainable cyber infrastructure for scalable underwater operations are listed here:

1. Unified Infrastructure Communications and Networking: The team also points out some potential directions for underwater cyber infrastructure solutions:

1.1 How to take advantage of the SMART (Scientific Monitoring And Reliable Telecommunications) submarine cable system and add underwater PNT, wireless communications, AUV support, and sensing capabilities? Innovations are called to provide such multi-purpose services with minimum impacts on wildlife and the ocean environment while being cost-effective so that the system can scale up to basin coverage.

1.2 How to provide PNT services without increasing sound pollution underwater? One potential direction is to utilize the quantum compass for underwater GPS; another direction is to utilize communication signals and machine learning for navigation and localization services as well as sense.

1.3 There are many areas that technologies based on electromagnetic waves (both for communication and local GPS) offer competitive or even superior performance with smaller environmental pollution and lower required size, weight, and power. This is a relatively unexplored area of research.

1.4 The team recognized that one of the prioritized research topics is providing reliable and sustainable power supplies to underwater assets and activities. Potential topics include energy harvesting from the ocean environment, novel battery technology and power management for long-term deployment. Multiple agencies including NSF have many existing programs that support underwater energy innovations, technology development, and field applications. It is wise to take the constraints of the existing and emerging energy solutions into account when proposing works in underwater cyber infrastructure.

2. Sensor and IoUT Technology:

2.1 Innovations in sensing technologies and biodegradable materials and circuits may be utilized to monitor the underwater environment and reduce the ocean garbage from lost instruments and other assets. With the current level of 10% loss of ocean mobile assets, the accumulation of microplastics and its impact will not be negligible.

2.2 Monitoring other environmental aspects, for example, pH, CO_2, chemical pollutants, bacteria, etc., also remains a challenge in terms of sensitivity, accuracy, and in situ capability. Miniaturization, power, and weight are also significant limitations to integration of new sensors onto mobile platforms. Some of the topics are also listed in the report of NSF 2018 Seafloor Instrumentation Workshop.

2.3 Develop task-oriented UIoT infrastructure/network architecture (e.g., underwater pollutant detection, aquaculture and fishing, offshore oil and gas infrastructure health monitoring, etc.) by integrating novel underwater sensing, marine robotic, and short/long-range underwater communications techniques.

3. Marine Robotics:

3.1 Establish principles and design methodologies that utilize marine robots as mobile sensor platforms to collect controlled Lagrangian data streams for a broad scope of spatial-temporal processes underlying ocean and environmental phenomena. Encourage the integration of oceanographic models and data-driven models with marine autonomy under realistic constraints on data rate, localization accuracy, sensor capability, and power budget.

3.2 Leveraging communication, networking, localization, and power support provided by the underwater cyber-infrastructure, promote technology advancements towards persistent autonomy for marine robots to maintain a longer-term presence in three-dimensional ocean environments, including the surface, the bottom, and the water column.

3.3 Develop cost-effective open-source hardware and software systems, maintain shared testbed and common datasets to lower the barrier for broader participation from the community in research and education activities on marine robots.

3.4 Extend the scope of applications of marine robots in the blue economy. Form partnerships with industry and research institutions focusing but not limited to: aquaculture and fishing, environmental monitoring and cleaning, underwater data centers, shipping and transportation, oil and gas.

Appendixes

Appendix A. Detailed Workshop Schedule and List of Presentations

DAY 1: TUESDAY JAN. 12TH, 2021

Session 1: Ocean Science Perspectives: Needs and Challenges

10:00 am - 10:10 am Opening Remarks

10:10 am - 10:40 am keynote speech + Q&A:

- "Essential Elements for Underwater Cyber Infrastructure" -- Bruce Howe (University of Hawaii)

10:45 am - 11:25 am, four short talks

- "Looking forward - Marine Robotics and High-Resolution Mapping in the Ocean" -- Hanumant Singh (Northeastern University)
- "Summary of 2018 NSF Seafloor Sensing Workshop and Recommendations" -- Christopher Parrish(Oregon State University)
- "The JANUS Underwater Communication Standard" -- Joao Alves (CMRE Italy)
- "Underwater Communication Signal from the Perspective of Ocean Noise Management" -- Shane Guan (Bureau of Ocean Energy Management)

11:30 am - 11:55 am, seven 3-min lightning talks pre-recorded lightning talks video

- "Why Every Seafloor Seismic and Geodetic Sensor Needs to Be Connected to the IoUT" -- William Wilcock (University of Washington)
- "Ocean Observing Systems and Resident Underwater Robotics" -- Dana Manalang (APL, University of Washington)
- "Acoustic Propagation, Acoustic Navigation, Arctic Oceanography" -- Lora Van Uffelen (University of Rhode Island)
- "Pushing the (Glider) Envelope: Glider-based Navigation and Subsea Current Measurements" -- Sarah Webster (APL, University of Washington)
- "Augmenting Scientific Research with an Underwater Internet of Things" -- Jules Jaffe (Scripps Institute of Oceanography)
- "Real-time Passive Acoustic detection of Endangered North Atlantic Right Whales Using Autonomous Underwater Technology" -- Genevieve Davis (NOAA)
- "Ropeless fishing networks" -- Mark Baumgartner (WHOI)

11:50 am - 12:50 pm breakout room discussion

Lunch break

Session 2: IoUT Hardware, Electronics, and Applications in Extreme Environments

1:30 pm - 2:00 pm keynote speech + Q&A

- "Building the Internet of Underwater Things" -- Fadel Adib (MIT)

2:05 pm - 2:35 pm, two short talks

- "New Directions in Underwater Communication Electronics" -- Santanu Das (ONR)
- "State-of-the-art Acoustic Telemetry for Studying Aquatic Animal Behavior and Survival: Current Capabilities and Future Advances" -- Daniel Deng (PNNL)

2:40 pm - 3:10 pm nine 3-min lightning talks pre-recorded lightning talks video

- "Underwater Acoustics Research Supporting the IoUT" -- Andrew Barnard (MTU)
- "Challenges and Opportunities in Ocean Sensing" -- Xuejue 'Sophie' Wang (Uconn)
- "Blue Energy to Power the Blue Science and Economy" -- Lei Zuo (VT)
- "Efficient Ultra-Low Frequency Transmission with Magnetic Pendulum Arrays for Underwater Applications" -- Ethan Wang (UCLA)
- "A Mechanically Based Magneto-inductive Transmitter with Electrically Modulated Reluctance" -- Nader Behdad (WISC)
- "Magnetic Induction-based Underwater Communications" -- Zhi Sun (Buffalo)
- "Riding the Stress Wave: integrated monitoring and Communications for Offshore Pipelines" -- Miao Pan (UH)
- "Electromagnetic waves for Communication and Navigation Underwater" -- Majid Manteghi (VT)
- "Cybersecurity is an extra-functional requirement (XFR)" -- John Jorgensen (ABS)

3:10 pm - 4:10 pm breakout room discussion

4:15 pm - 4:30 pm Day 1 concluding remarks

DAY 2: THURSDAY JAN. 14TH, 2021

Session 3: Underwater Communications, Signal Processing, and Networking

10:00 am - 10:30 am keynote speech + Q&A:

- "Underwater Communications, Signal Processing, and Networking" **--** Milica Stojanovic (Northeastern University)

10:35 am - 11:05 am three short talks

- "Status of Underwater Acoustic Communications" -- Bob Headrick (ONR)
- "Infrastructure to Advance Mobile Underwater Wireless Networking Research" -- Aijun Song (University of Alabama)
- "Networking and Acoustic Communications at NRL" -- Lloyd Emokpae (NRL)

11:15 am - 11:35 am, six 3-min lightning talks

pre-recorded lightning talks video

- "Signal Processing and Communication Systems, Underwater Acoustics and Acoustic Communications" -- Andy Singer (UIUC)
- "Underwater Acoustic Communications and Networking" -- Zhaohui Wang (MTU)
- "Underwater Wireless Communications & Networking" -- Prasad Anjangi (Subnero Inc.)
- "Network-Layer Challenges in Underwater Wireless Communications" -- Xiaoyan Hong (University of Alabama)
- "Underwater Wireless Networking" -- Mohamed Younis (UMBC)
- "Deep Reinforcement Learning for Underwater Acoustic Networks" -- Rosa Zheng (Lehigh University)

11:40 am - 12:50 pm breakout room discussion

Lunch break

Session 4: Marine Robotics and Artificial Intelligence for IoUT

1:30 pm - 2:00 pm keynote speech + Q&A

- "Underwater Communication for Marine Robotics" -- Mandar Chitre (NUS Singapore)

2:05 pm - 2:45 pm, four short talks

- "Applications of Acoustic Communications" -- Lee Freitag (WHOI)
- "Enabling Undersea Persistent Autonomy" -- Nina Mahmoudian (Purdue)
- "Marine Robotic Networks: From Platforms to Services" -- Fumin Zhang (Georgia Tech) and Catherine Edwards (U Georgia)
- "Ocean Thermal Energy to Power Underwater Systems" -- Yi Chao (Seatrec)

2:50 pm - 3:10 pm, four 3-min lightning talks pre-recorded lightning talks video

- "Marine Vehicles and Marine Environments" -- Geoff Hollinger (Oregon State University)
- "The Naviator: An Unique Multirotor Unmanned Air/Underwater Vehicle" -- Javier Francisco Diez (Rutgers, The Navigator)
- "Underwater Localization, Coral Classification, Mapping, Exploration, and Coverage" -- Ioannis Rekleitis (U. of South Carolina)
- "Robotic Vehicle System for Novel Ocean Obs" -- Joao Sousa (University of Porto) and Kana Rajan (University of Porto/SIFT LLC)

3:15 pm - 4:15 pm breakout room discussion

4:15 pm - 4:30 pm closing remarks

Appendix B. Slides of Keynotes

Session 1 Keynote Speech

"Essential Elements for Underwater Cyber Infrastructure"
-- Bruce Howe (University of Hawaii)

Essential Elements for Underwater Cyber Infrastructure

Bruce Howe
Ocean and Resources Engineering
School of Ocean and Earth Science and Technology
University of Hawaii
Honolulu, Hawaii, USA

Advancing Underwater Cyber Infrastructure for Blue Science
12 January 2021

Challenges for underwater CI -

- Need for sustained global scale ocean observing
- Requires long term solutions for tech, maintenance, funding, …

- Here:
  - Not considering localized short term science – for others
  - Emphasize interior, deep(er) ocean, removed from sea surface and EM

Essential elements for underwater CI

- Power
- Communications
- PNT (Positioning, Navigation, Timing)
- ALL f(x,y,z,t)

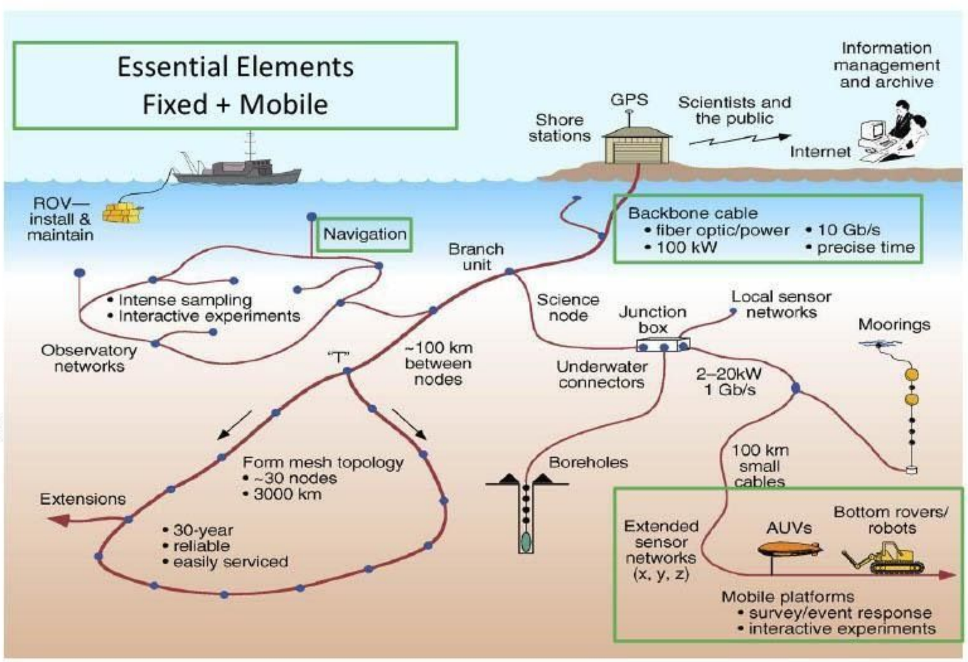
Essential elements for underwater CI

- In the ocean, fundamental limitations and caveats
  - On and near the surface access to power (waves, solar, etc), and with EM, comms and GPS is possible – “easy,” BUT air-sea interface extreme
  - Difficult to extend from surface down into interior – no long-term power, EM -> acoustics need power
  - Power is fundamental limitation - Adequate power can solve some/many problems

Outline

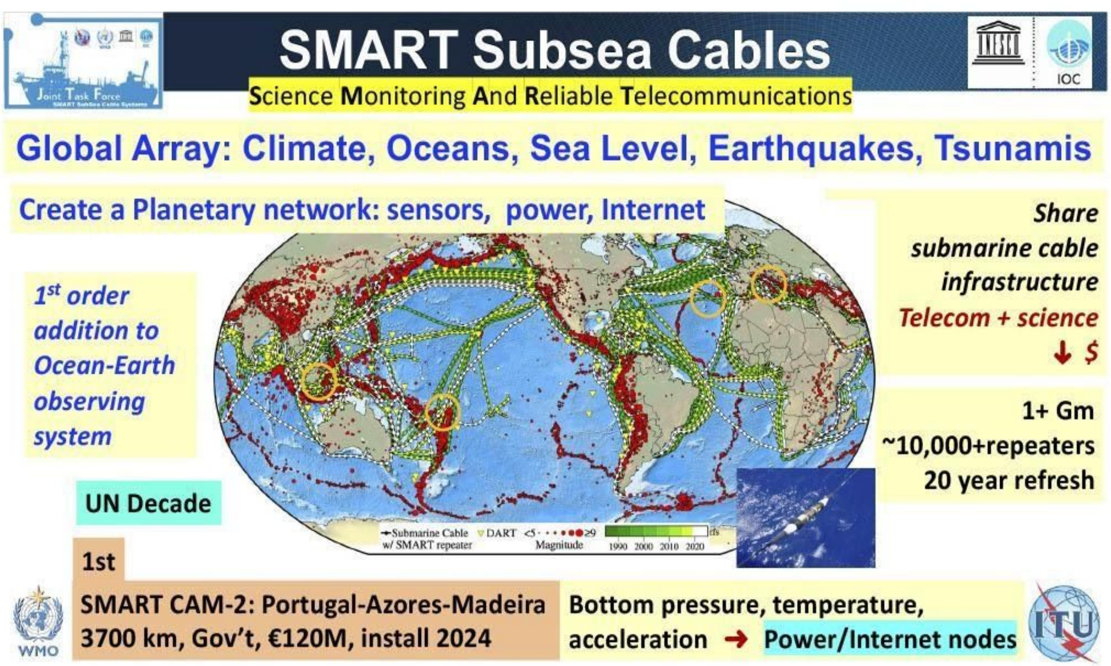
- Need to consider ALL (often intertwined)
  - Energy/Power – the fundamental need
    - Cables, OTEC, fuel cells, tankers, docking
  - Where am I? What time is it? PNT
    - Timing, positioning/navigation
  - Communications
    - Acoustics, optical, hybrid
- The Challenge

NEPTUNE
c. ~2000



Elements that can contribute – OceanObs'19 Recommendations

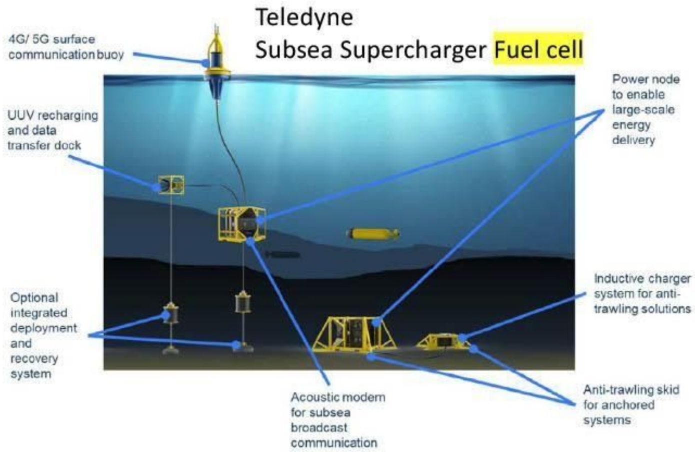
- Transition telecom+sensing SMART subsea cables, pilots to global implementation, for climate, ocean circulation, sea level monitoring, and tsunami and earthquake early warning and disaster risk reduction.
- Pilot multipurpose acoustic network - passive monitoring, tomography, underwater positioning and communication in Arctic observing system, eventually to global coverage.



Power/energy possibilities

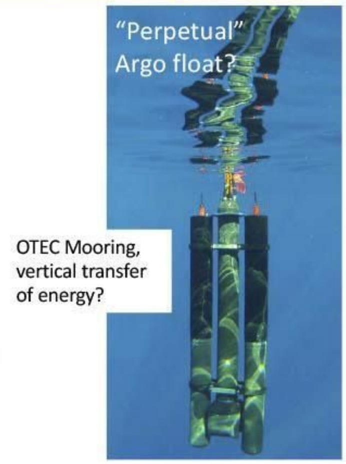
Batteries

Sustained? Cost to maintain?



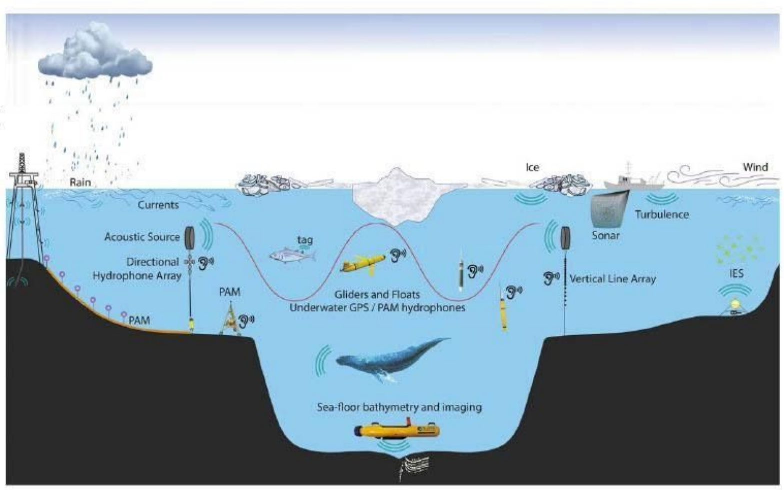
SeaTrec OTEC

Ocean Thermal Energy Conversion



Multi-purpose acoustic network

- Positioning, Navigation, Timing (PNT)
- Communications
- Tomography
- Active
- Passive
- Scaleable – long range

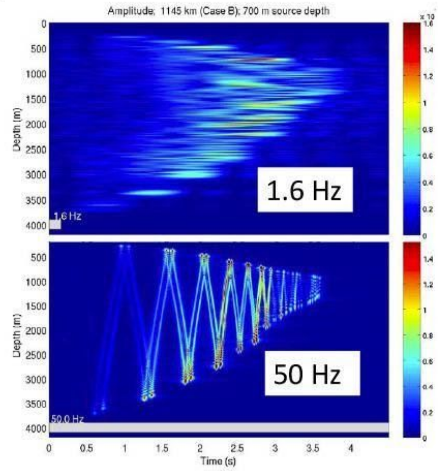


Observing the Oceans Acoustically. Front. Mar. Sci. 6:426. doi: 10.3389/fmars.2019.00426, 2019

Need broadband for all applications

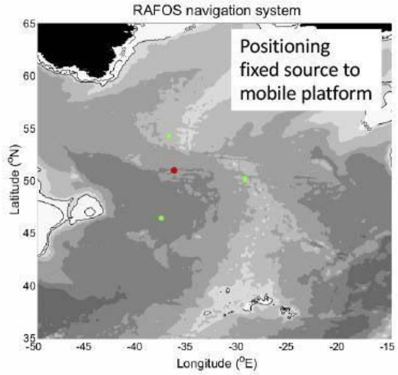
- Duda et al. 2006
- Time fronts
- RAFOS 1.6 Hz – 0.5 sec errors
- RAFOS2 50 Hz ~ 10 ms.

- Analogy – LORAN and GPS



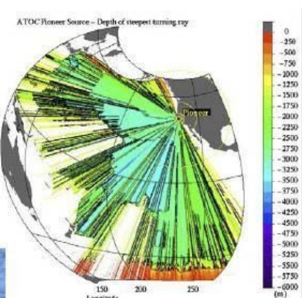
Acoustic Network - Sources

- Realtime undersea positioning a la GPS – **AUVs!!!**
- Small number of strategically located sources



GeoSpectrum C-Bass

Matt Dzieciuch



ATOC cabled source coverage

Marine mammals – no significant impacts

Low Frequency source moored in Arctic

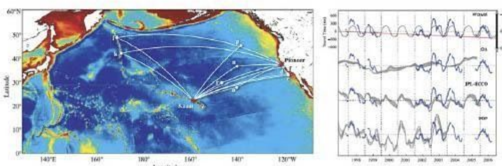
Acoustic Network

HIFT
9 Mm
Doppler
11 bit/s

- CTBTO coverage - receivers
- ATOC (Acoustic Thermometry of Ocean Climate)
- Measuring the temperature of the ocean at the speed of sound – 1 hour across the Pacific
- Highly accurate spatial averages
- Future – handful of sources
- ALL receivers, fixed and mobile can participate
- A la GPS

Comprehensive Nuclear Test Ban Treaty Organization (CTBTO)

Hydroacoustic Stations Kevin Heaney

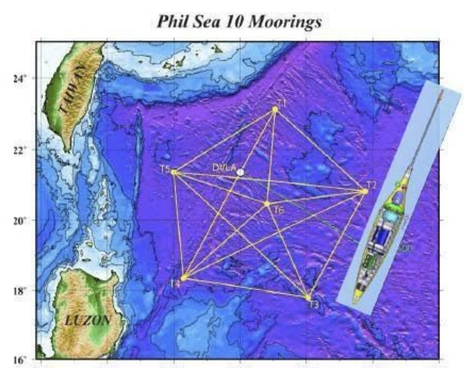


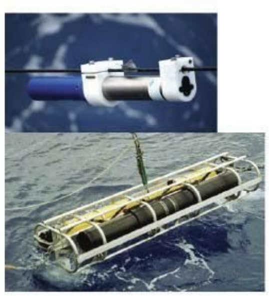
Brian Dushaw

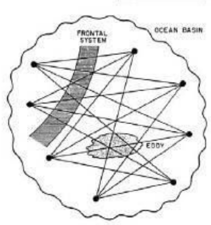
PhilSea10

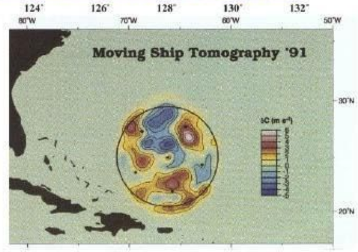
- Large, multi-purpose experiment
- Test gliders for nav and as moving receivers for tomography – N^2

Lora Van Uffelen will present
glider positioning results later today
Freitag, Webster related

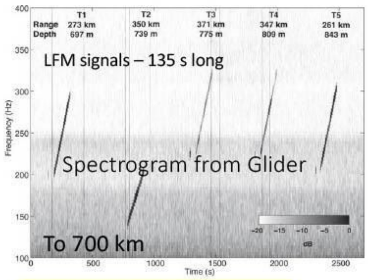


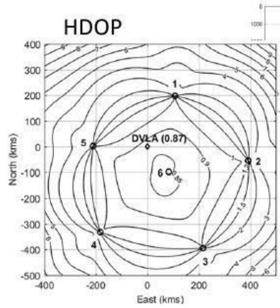


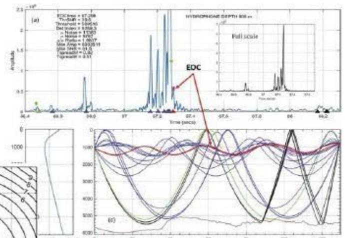




PhilSea – Positioning how good?







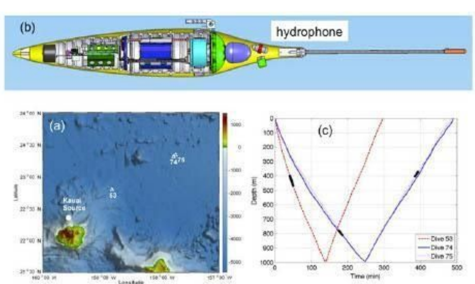
Using moored receiver data (known position)

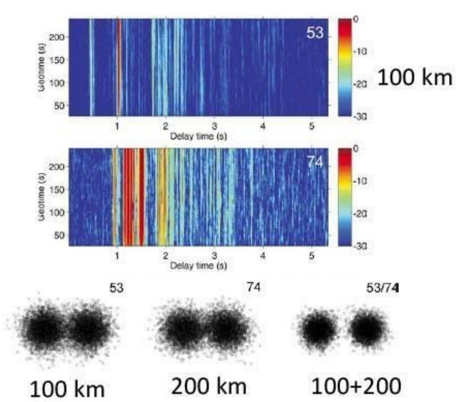
Deep ocean long range underwater navigation
P. Mikhalevsky et al., 2020

- 50 m achievable
- Steps to "underwater GPS" combined with tomography

Comms Coherence at long range

- Glider 100 and 200 km from Kauai ATOC source at 75 Hz, 37.5 Hz BW

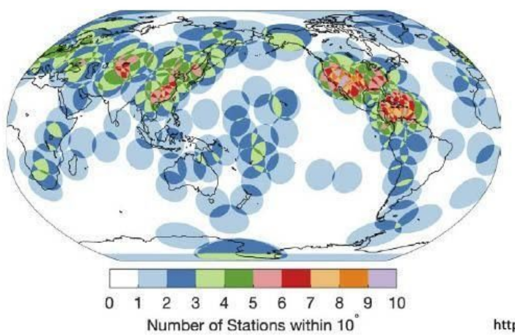


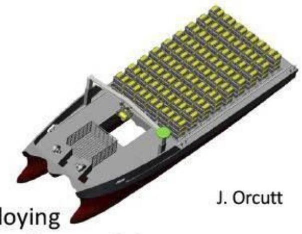


Song et al., 2014

Comms Gateways

One motivation:
Global Seismographic Network (GSN) coverage
White space = gaps to fill





Deploying
Ocean Bottom Seismometers

Sustained Maintenance?

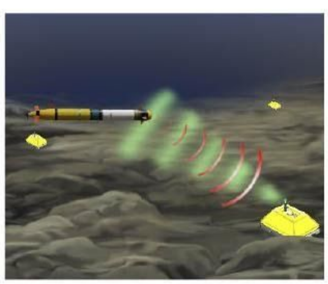
Seabed 2030 X-Prize ASV + AUV

https://www.esri.com/about/newsroom/blog/xprize-esri-partner-seafloor-mapping/

Comms Gateways

Optical modem can be used from a variety of platforms to communicate with shielded OBS. It can:

- Use an AUV (REMUS-600)
  - Endurance: 70 Hours at 3 knots
  - Range: 286 nautical miles
  - Depth: 600 meters
  - Communications: OTH Iridium



Shielded OBS with Integrated Optical and/or Acoustic Modems

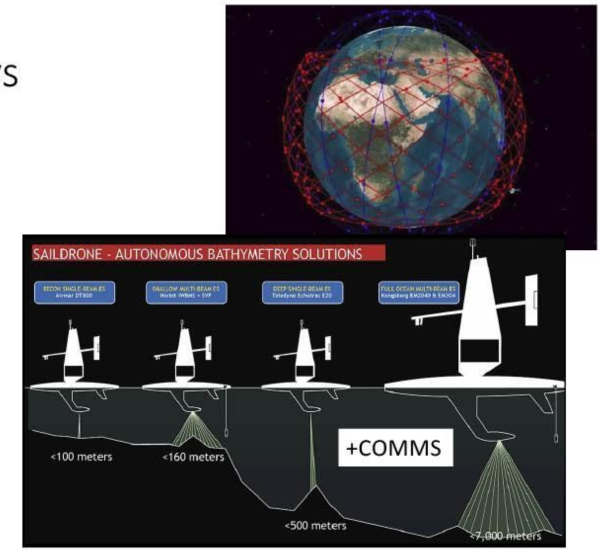
Sustained? Tankers?

	Optical	*Acoustic*
Data rate:	10-20 Mbits/sec	5 kbits/sec
Range:	150 meters	kilometers
Latency:	micro sec	msec to sec
Efficiency:	300k bits/J	1k bits/J

Slide credit: John Collins, WHOI

Comms gateways

- A la LEO satellites
- Large numbers of ASVs
- For subsea component:
  - KISS?
  - Power?
  - Real time comms?
  - Sustained?



Suggest foundation elements of global underwater CI ➔ SMART Cables + and Acoustics

- Globally distributed, reliable, ocean bottom mini-observatories
  - Ocean bottom measurements
  - Power/comms interface
  - Potential for docking, moorings, scalable acoustic network, etc

Cable re-use

- Global scale "acoustic GPS"
  - AUVs
  - Acoustic tomography – ocean temperature and heat content, using fixed and mobile platforms (N^2), and
  - Comms

SMART Cables for Observing the Global Ocean: Science and Implementation. Front. Mar. Sci. 6:424. doi: 10.3389/fmars.2019.00424
Observing the Oceans Acoustically. Front. Mar. Sci. 6:426. doi: 10.3389/fmars.2019.00426, 2019

Challenges for underwater CI

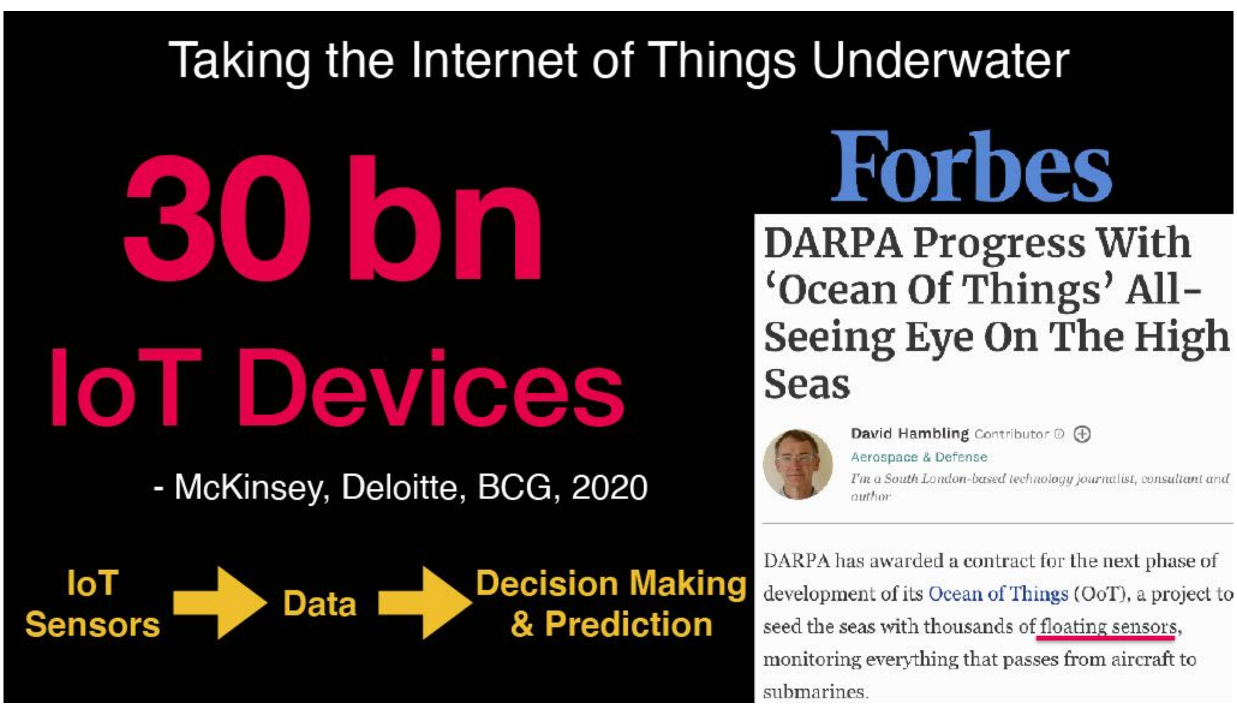
- How do we globally optimize the mix of fixed and mobile assets to achieve needed connectivity and coverage for the CI vision?
- Balance KISS, power/energy, real time, survivability, resilience, cost, personnel, scalable, …
- Need **global observing system planning**
- **This UCI community – step up to challenge!**

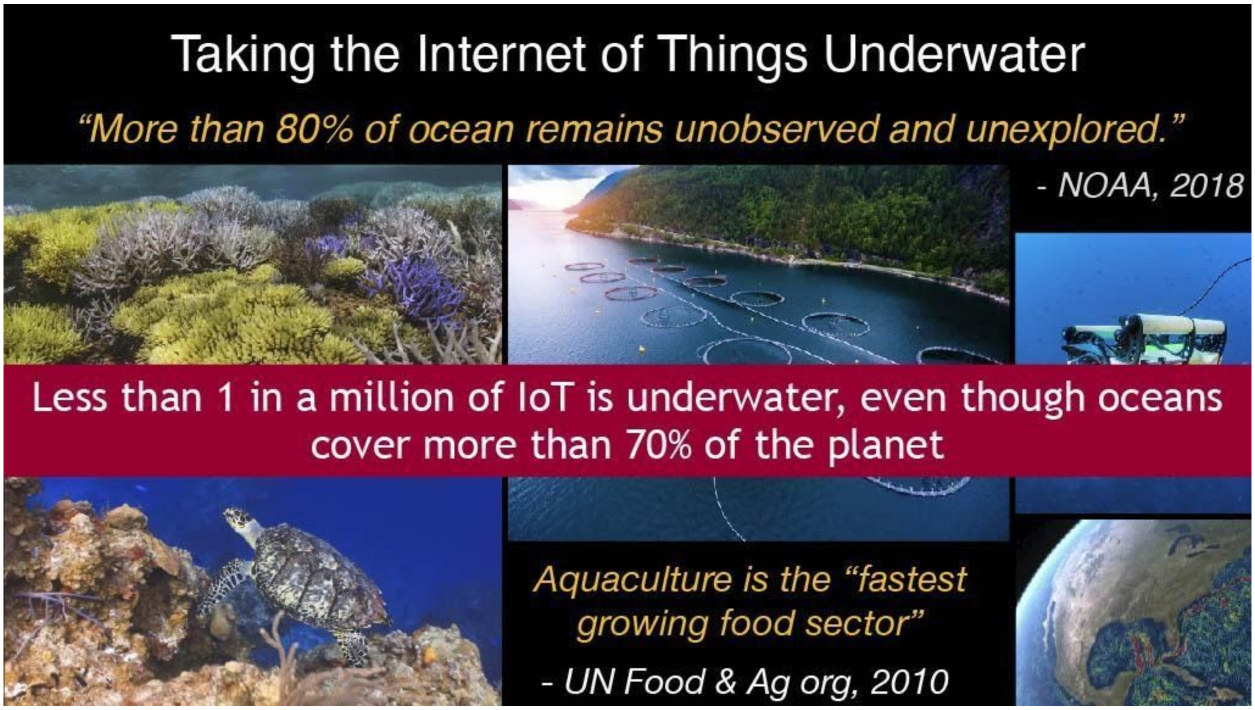
Thank you!

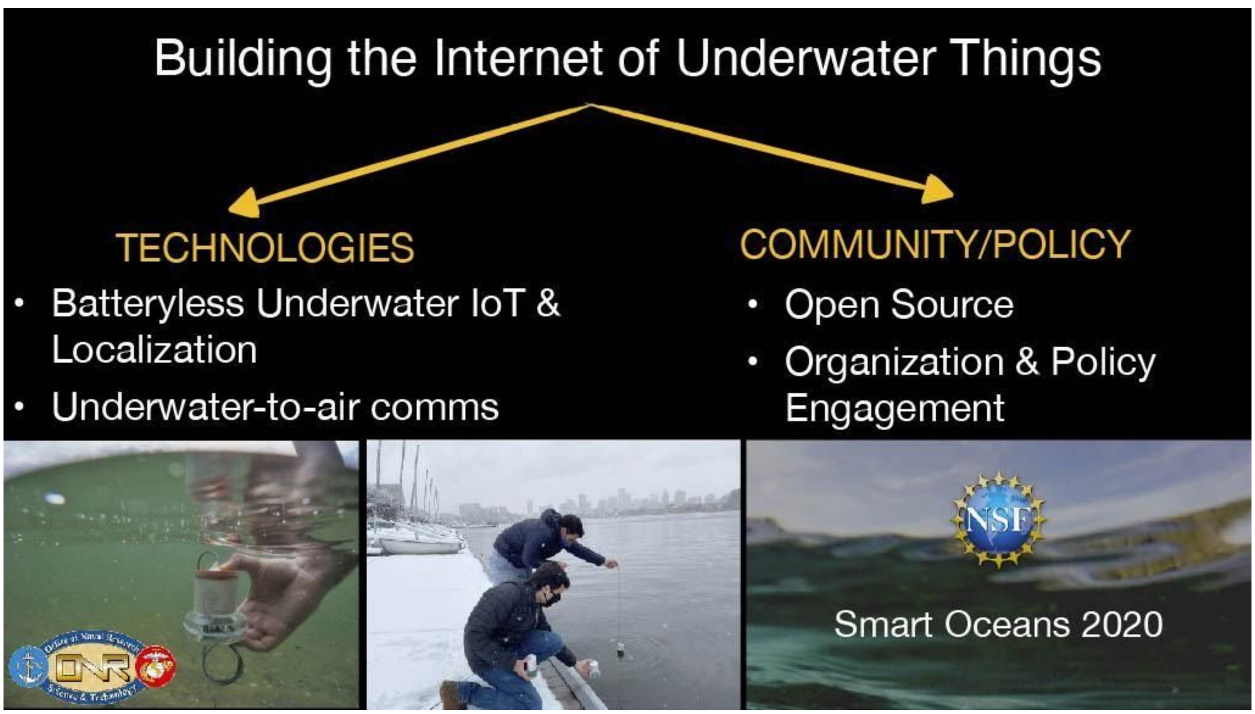
Questions?

Session 2 Keynote Speech

“Building the Internet of Underwater Things”
-- Fadel Adib (MIT)




Taking the Internet of Things Underwater
"More than 80% of ocean remains unobserved and unexplored."
- NOAA, 2018
Less than 1 in a million of IoT is underwater, even though oceans cover more than 70% of the planet
Aquaculture is the "fastest growing food sector"
- UN Food & Ag org, 2010


Building the Internet of Underwater Things
TECHNOLOGIES
• Batteryless Underwater IoT & Localization
• Underwater-to-air comms
COMMUNITY/POLICY
• Open Source
• Organization & Policy Engagement
ONR
NSF
Smart Oceans 2020

Building the Internet of Underwater Things

TECHNOLOGIES

- Batteryless Underwater IoT & Localization
- Underwater-to-air comms

COMMUNITY/POLICY

- Open Source
- Organization & Policy Engagement

Problem: Battery life of underwater sensors is extremely limited

Low-power underwater transmitters consume 10s-100s of Watts and cannot be recharged easily

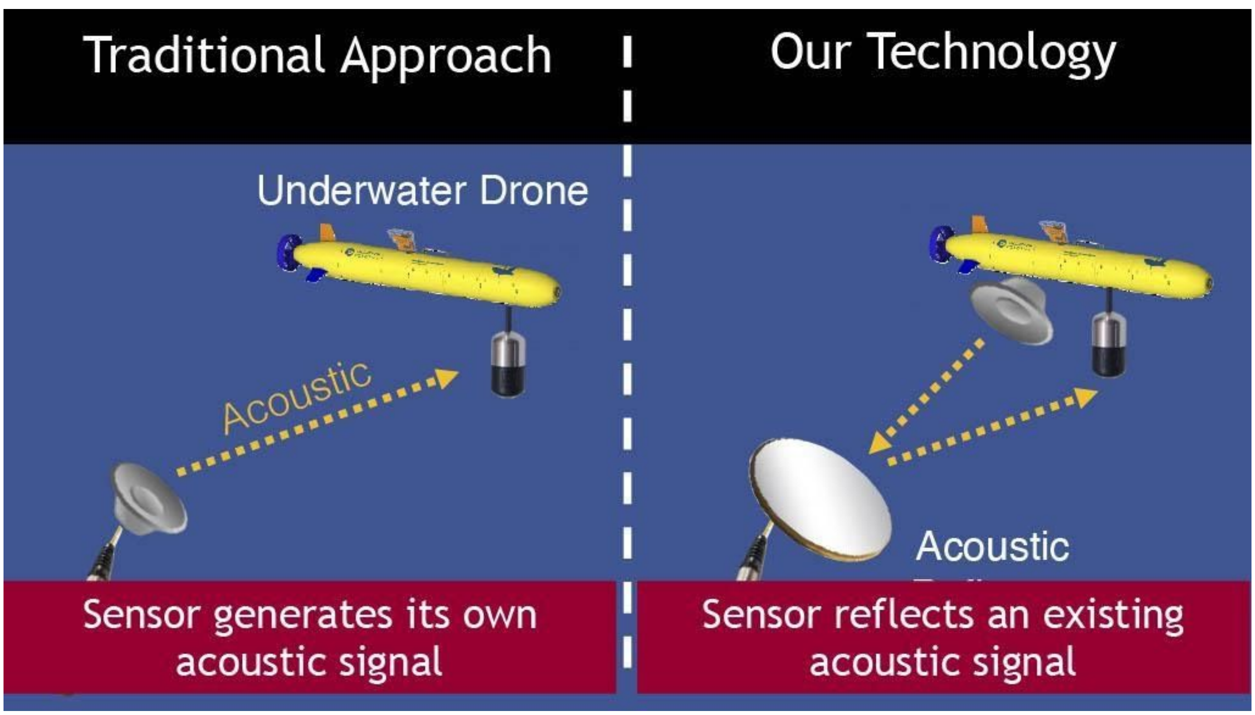
↓

Most state-of-the-art sensors for tracking marine animals only last for few hours or days

[Animal Biotelemetry'15, Scientific Reports'17]

Technology that Enables Underwater Backscatter (Batteryless) Networking

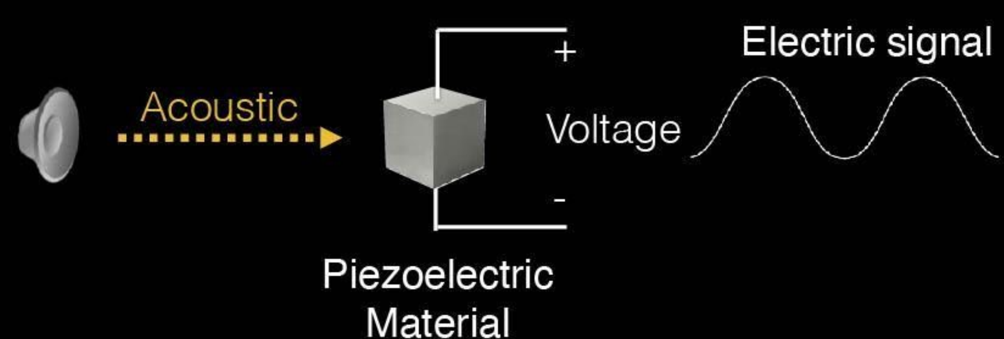
Published in: ACM SIGCOMM'19, ACM SIGCOMM'20, IEEE/MTS OCEANS'20, ACM HotNets'20

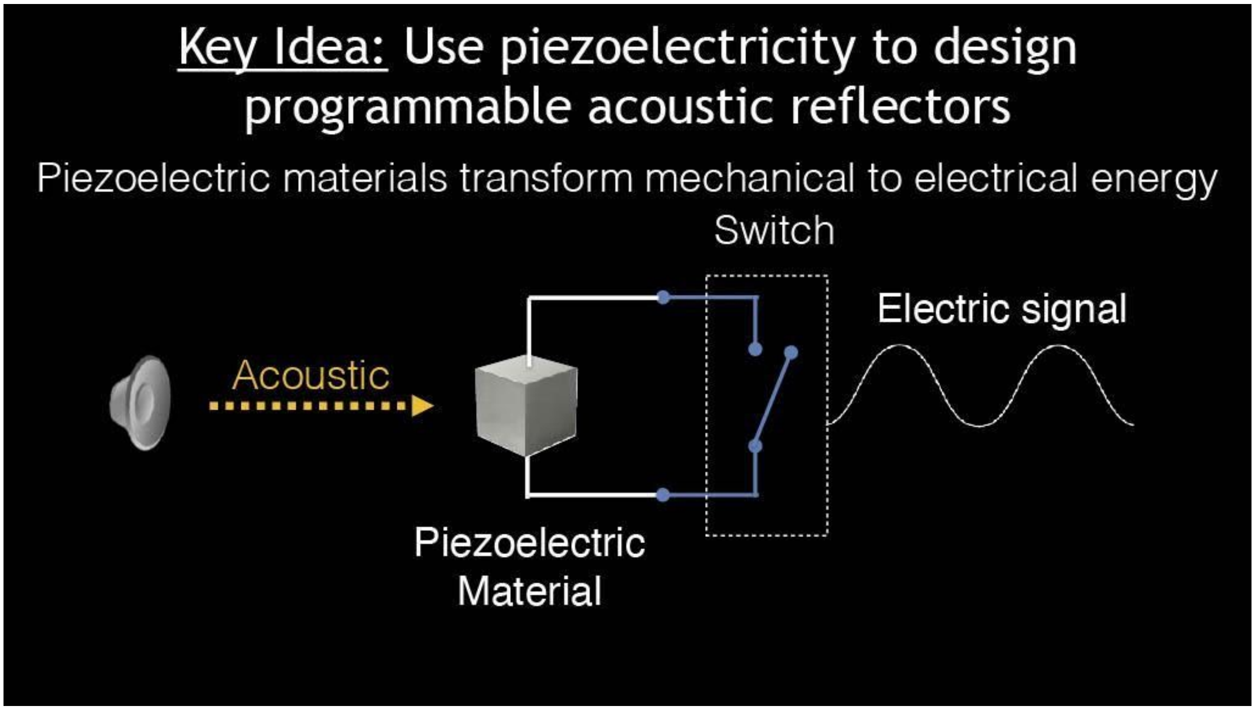


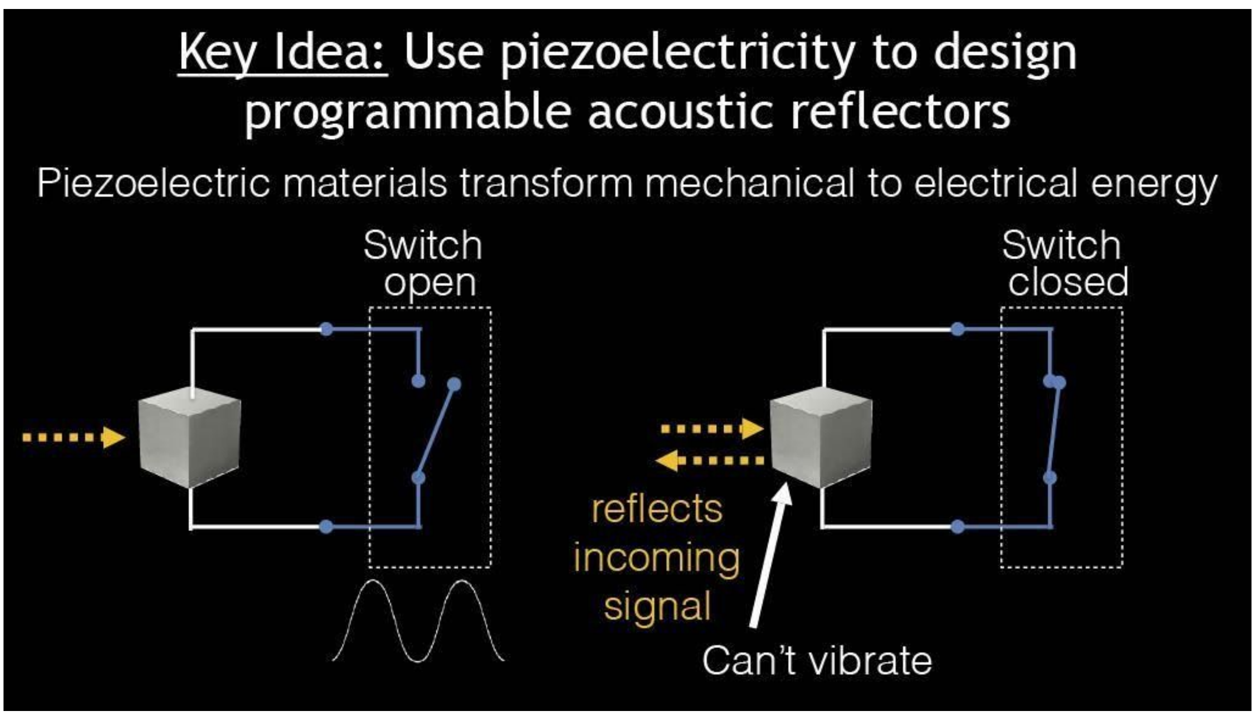
How can we control the reflections of acoustic signals?

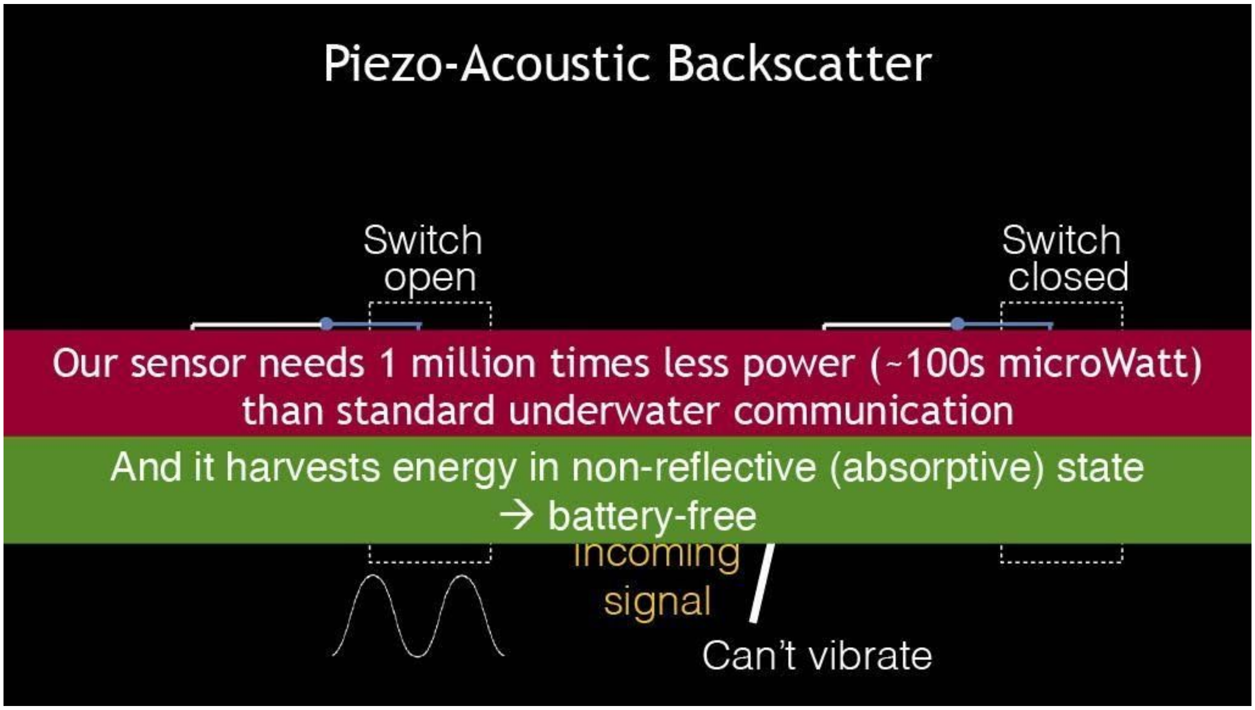
Key Idea: Use piezoelectricity to design programmable acoustic reflectors

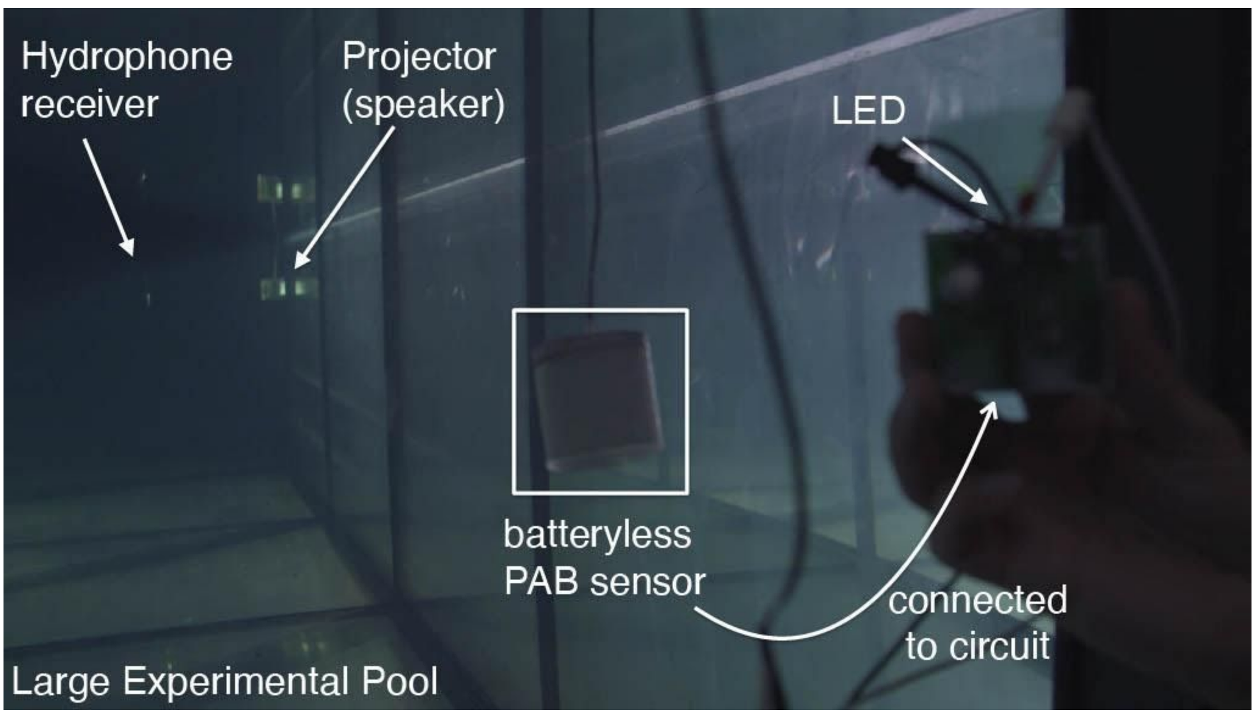
Piezoelectric materials transform mechanical to electrical energy

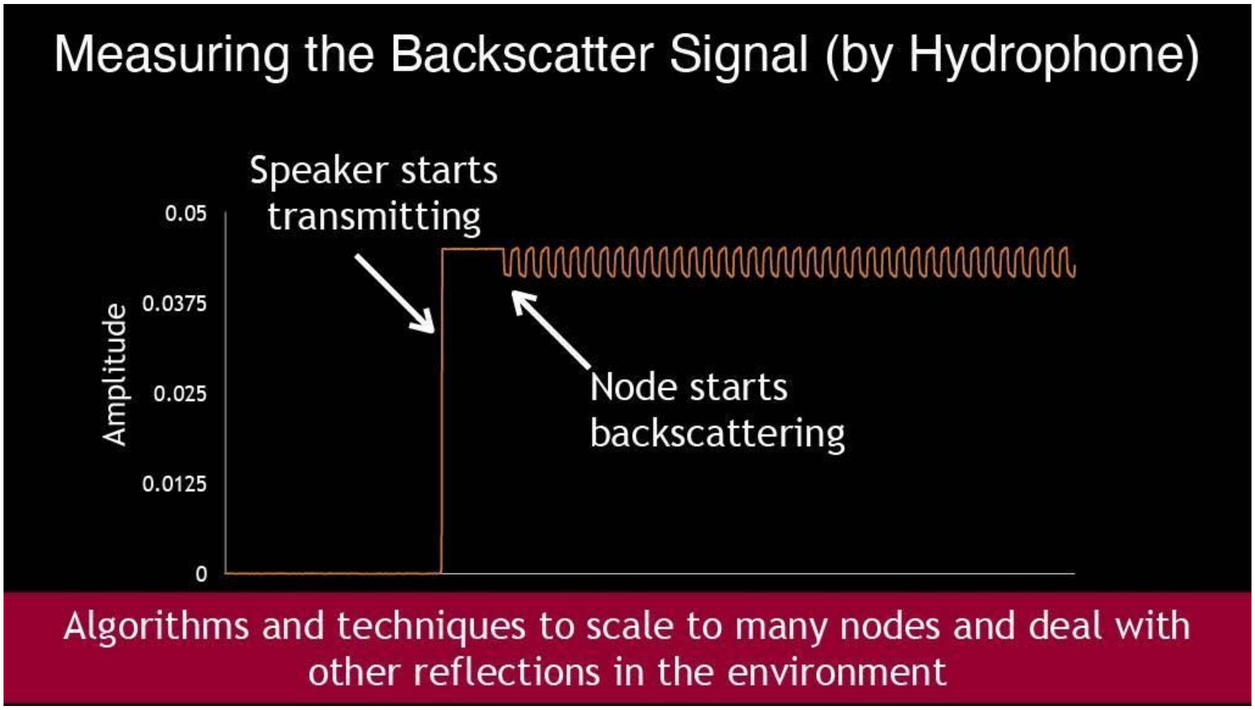


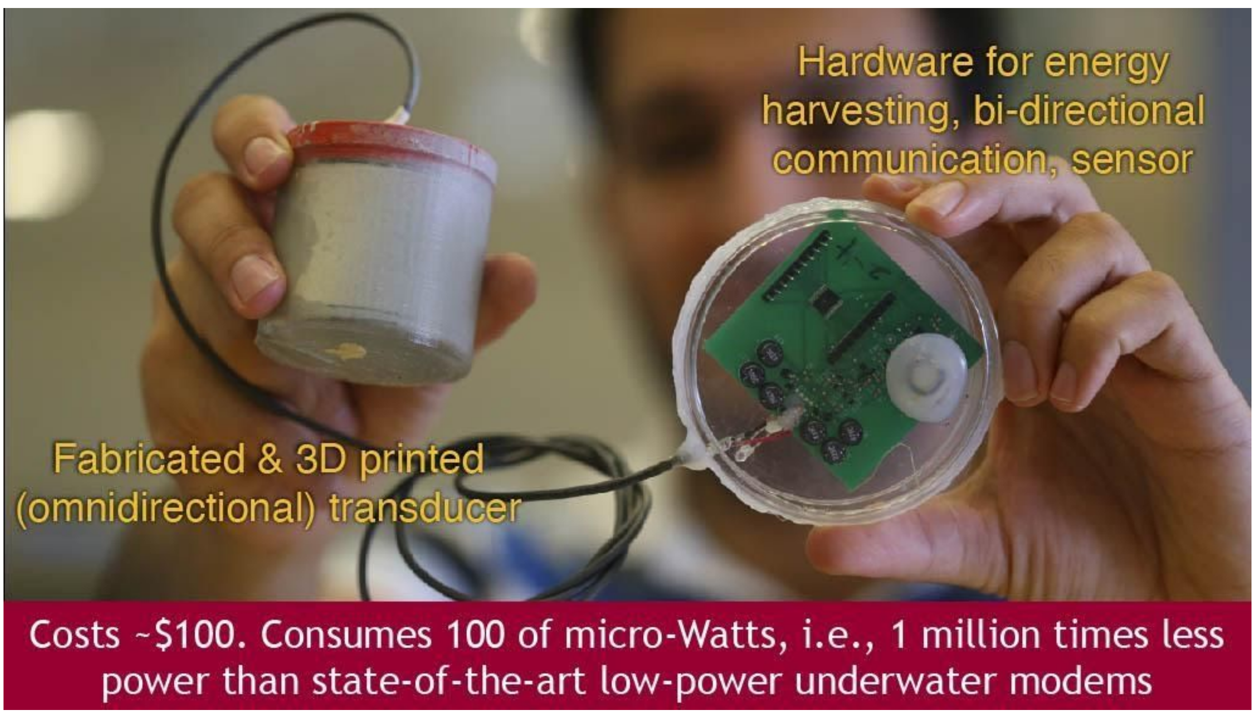

Key Idea: Use piezoelectricity to design programmable acoustic reflectors
Piezoelectric materials transform mechanical to electrical energy
Switch
Electric signal
Acoustic
Piezoelectric Material


Key Idea: Use piezoelectricity to design programmable acoustic reflectors
Piezoelectric materials transform mechanical to electrical energy
Switch open
Switch closed
reflects incoming signal
Can't vibrate


Piezo-Acoustic Backscatter
Switch open
Switch closed
Our sensor needs 1 million times less power (~100s microWatt) than standard underwater communication
And it harvests energy in non-reflective (absorptive) state
→ battery-free
incoming signal
Can't vibrate

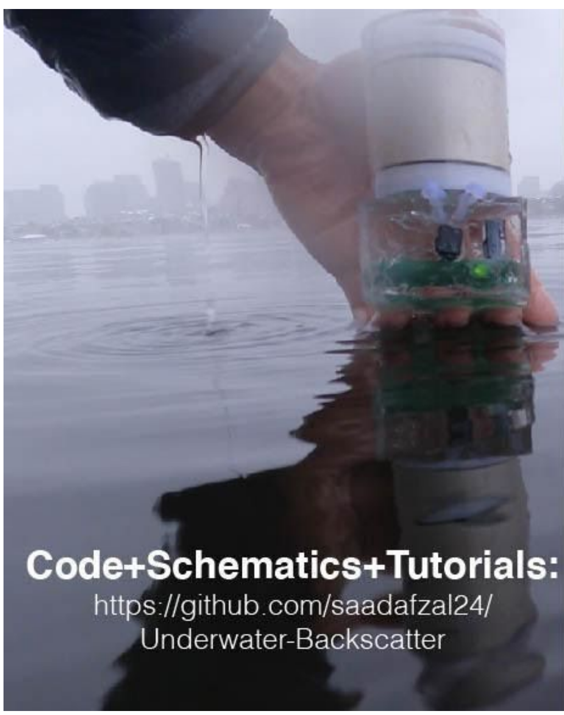

Hydrophone receiver
Projector (speaker)
LED
batteryless PAB sensor
connected to circuit
Large Experimental Pool


Measuring the Backscatter Signal (by Hydrophone)
Speaker starts transmitting
Node starts backscattering
Amplitude
0.05
0.0375
0.025
0.0125
0
Algorithms and techniques to scale to many nodes and deal with other reflections in the environment


Hardware for energy harvesting, bi-directional communication, sensor
Fabricated & 3D printed (omnidirectional) transducer
Costs ~$100. Consumes 100 of micro-Watts, i.e., 1 million times less power than state-of-the-art low-power underwater modems

Experimental Evaluation in River (with snow & rain)

- 500+ experimental trials at different ranges, throughputs, and number of nodes
- Throughput: 20kbps
- Range: 62m
- Concurrent nodes: 10
  - *before spatial reuse*
- Localization accuracy: centimeter-scale



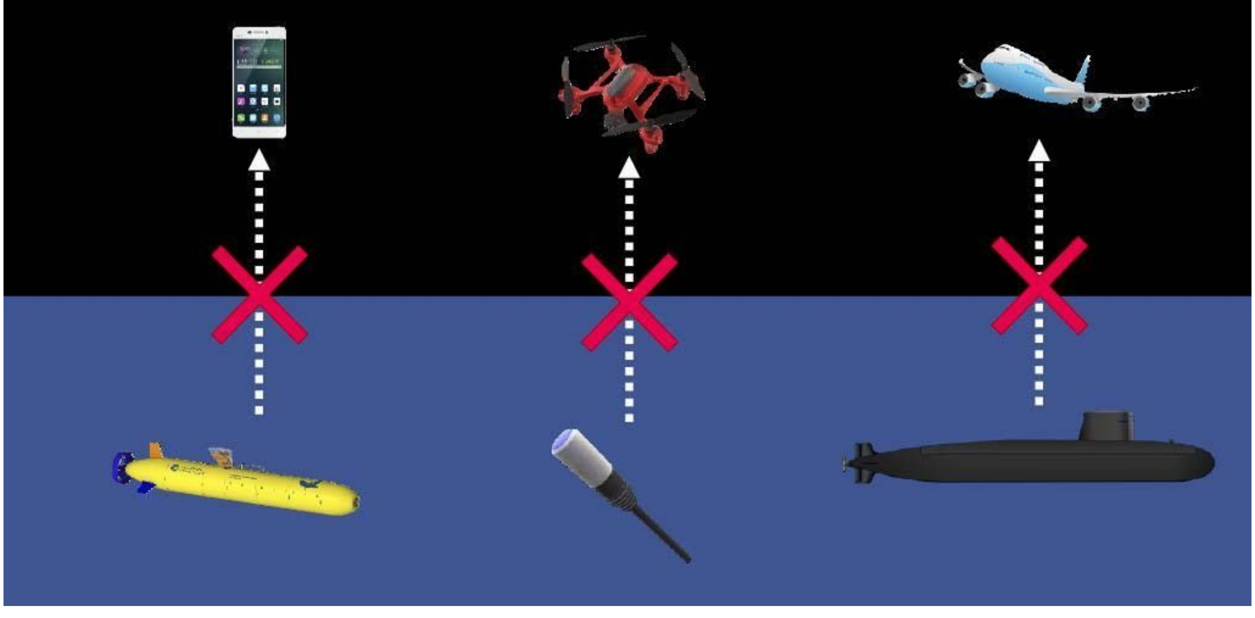
Open Problems in Underwater Backscatter

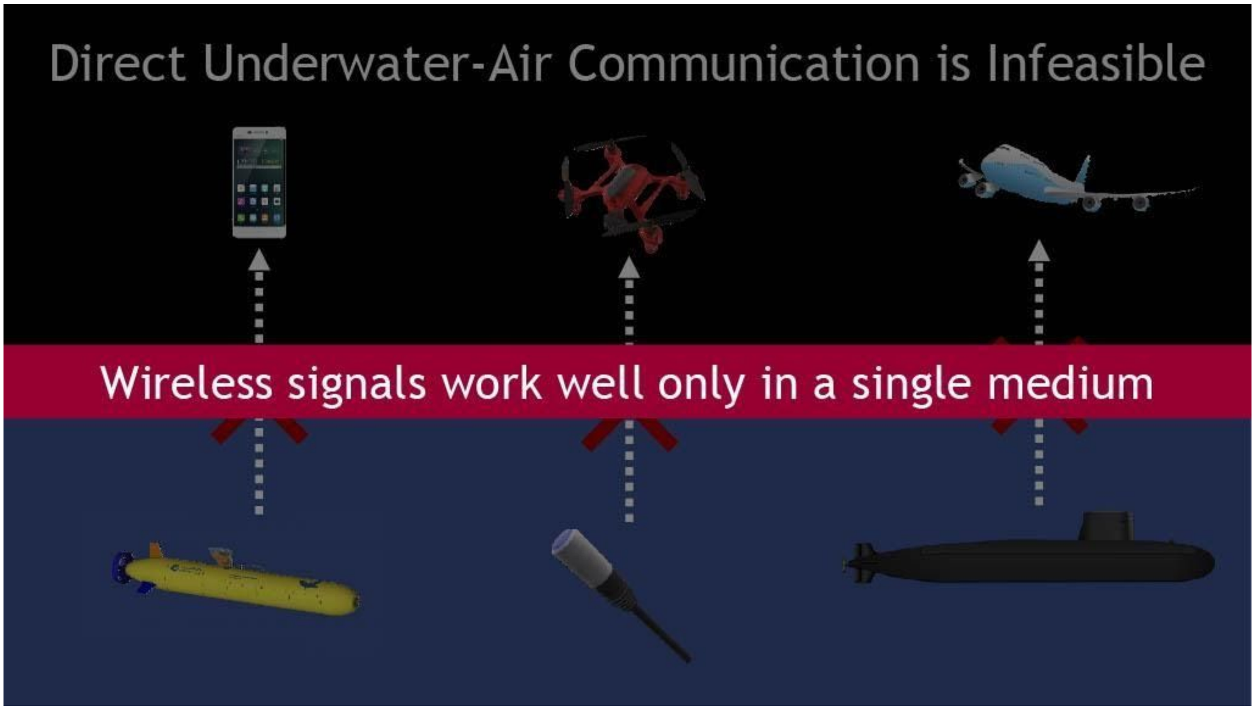
1. How can we scale the range and throughput?
2. Can we build multi-hop architectures?
3. Can we build accurate simulators?
4. How can we further reduce the energy consumption?
5. How can we go beyond net-zero power to zero pollution?

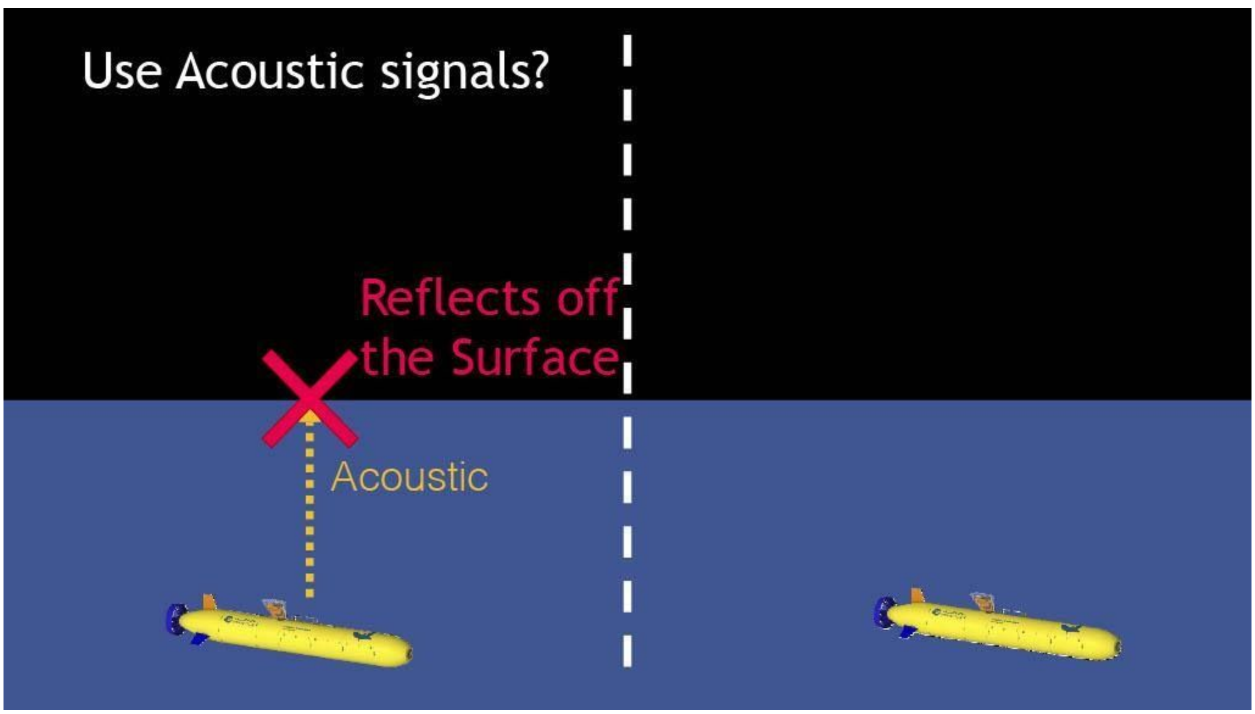
Localization, Navigation, Sensing

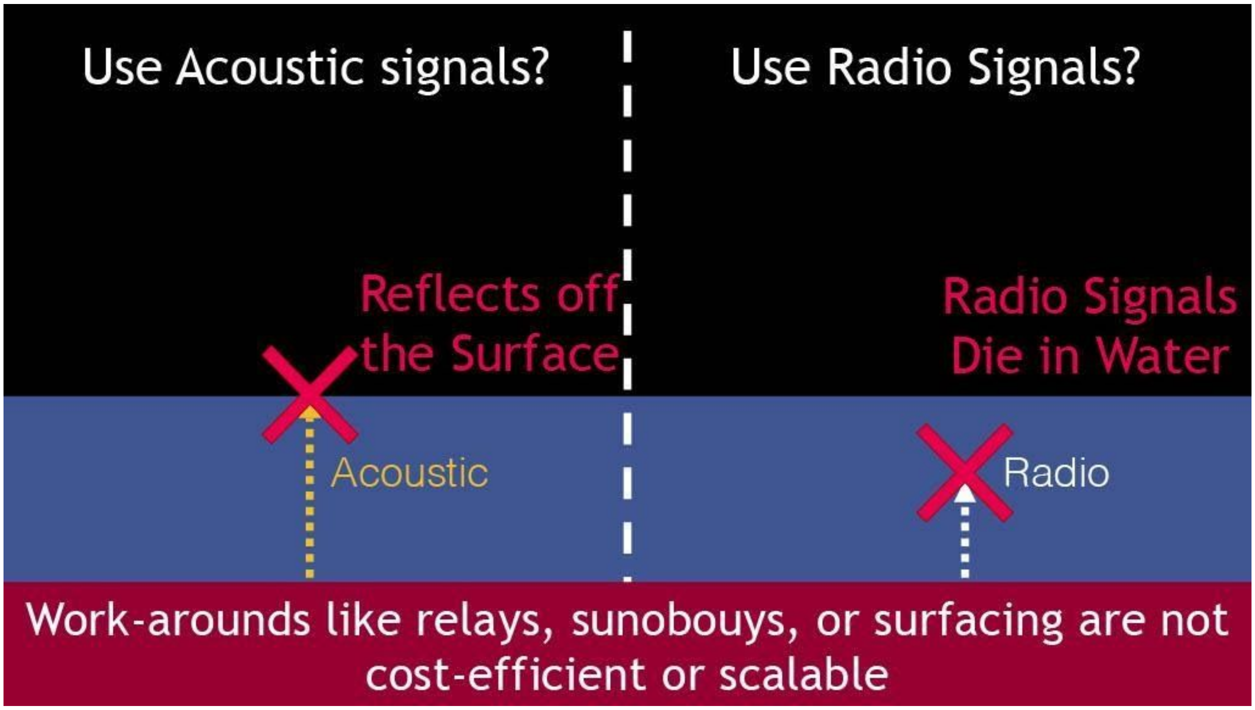
How can we send the sensed information to outside the ocean?

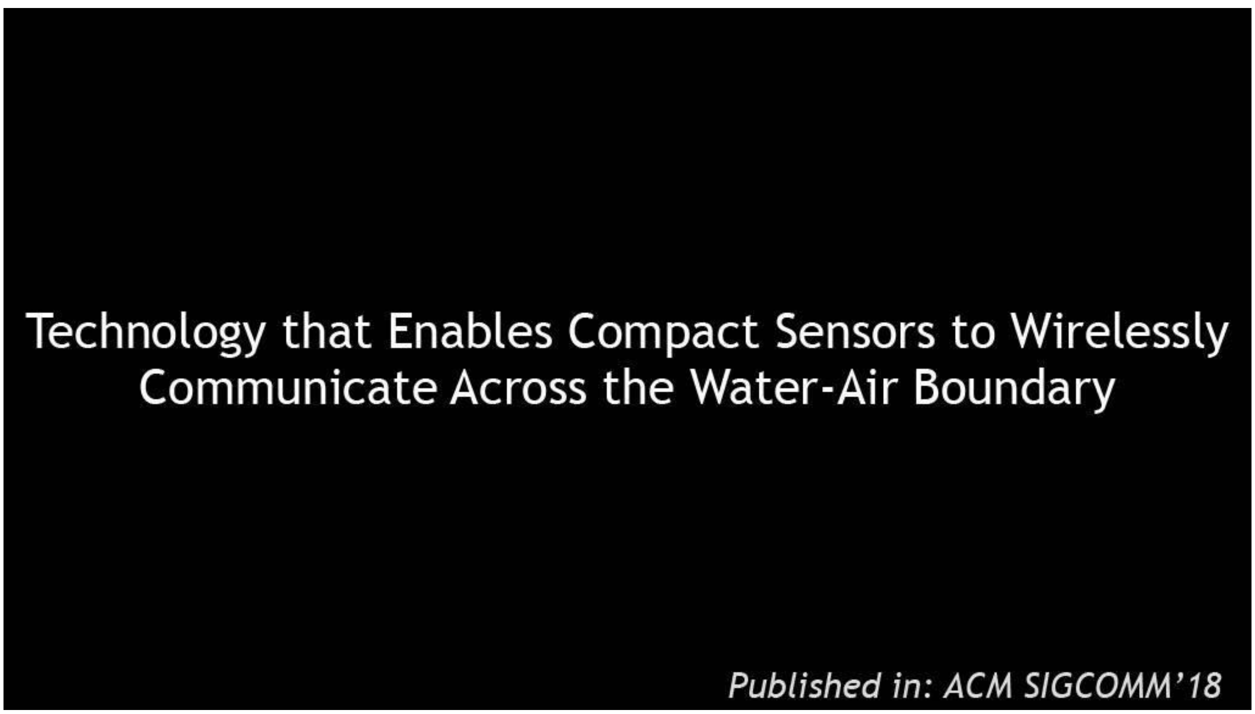
Direct Underwater-Air Communication is Infeasible

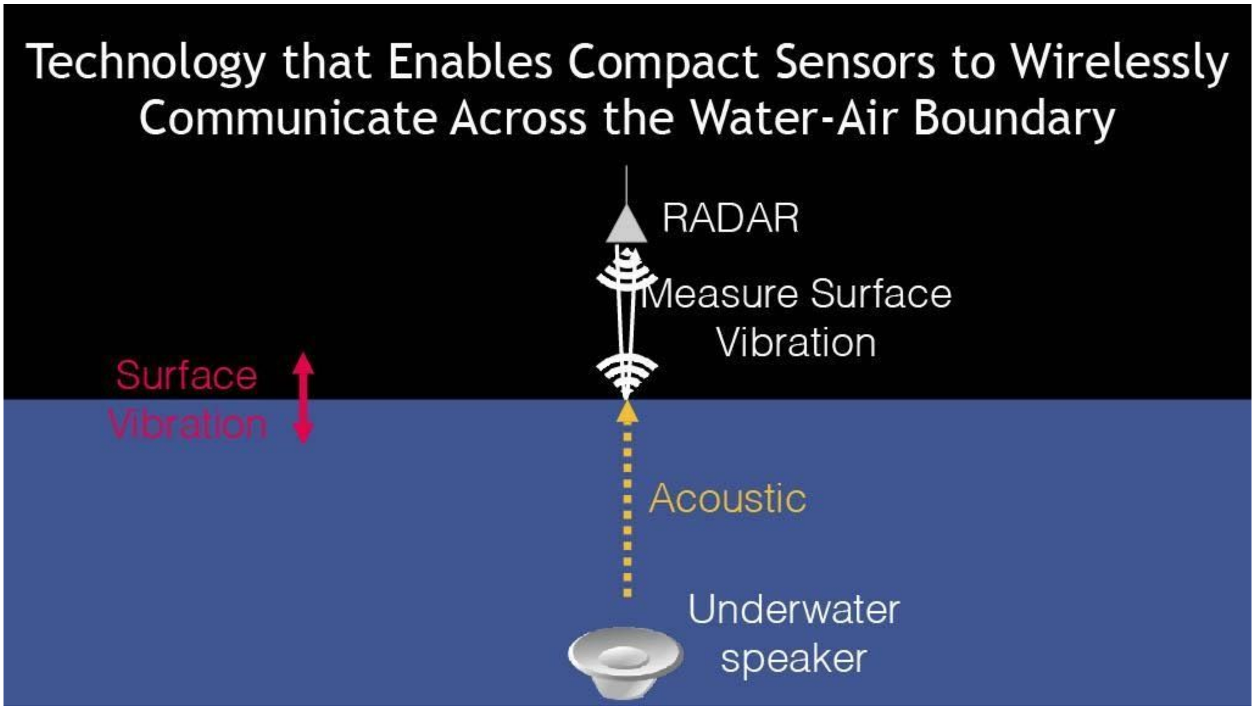


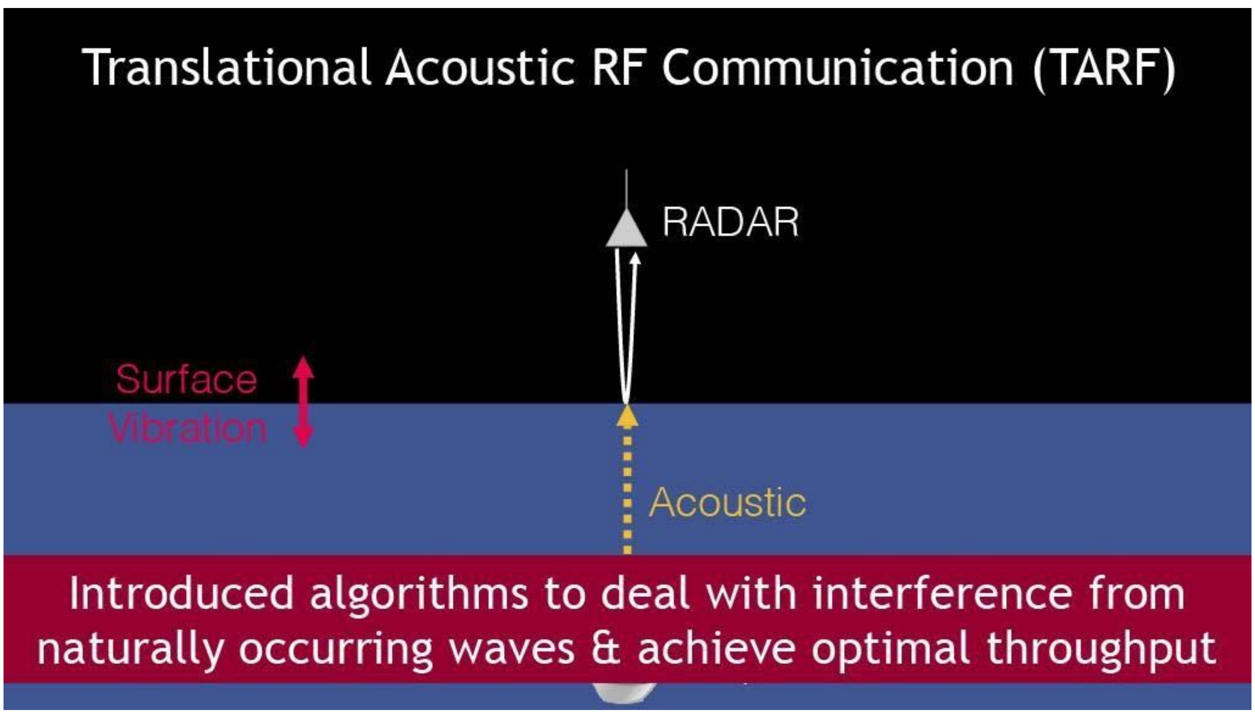

Direct Underwater-Air Communication is Infeasible
Wireless signals work well only in a single medium

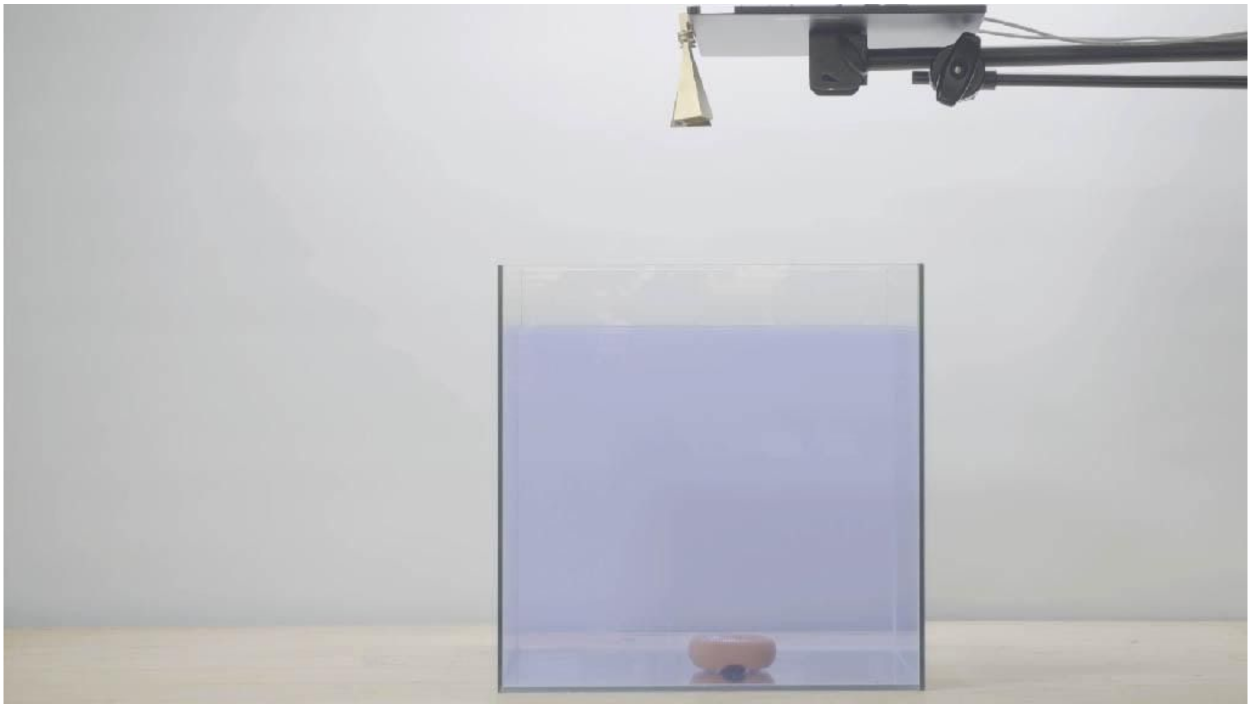

Use Acoustic signals?
Reflects off the Surface
Acoustic

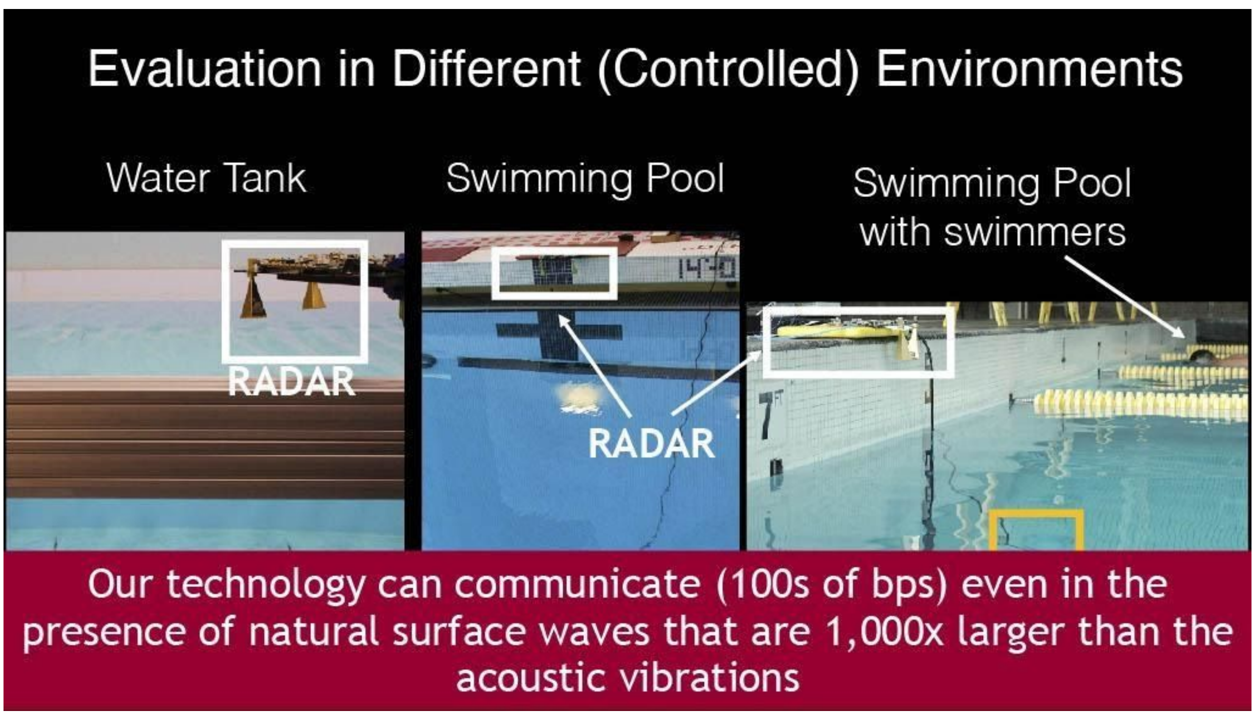

Use Acoustic signals?
Use Radio Signals?
Reflects off the Surface
Radio Signals Die in Water
Acoustic
Radio
Work-arounds like relays, sunobouys, or surfacing are not cost-efficient or scalable

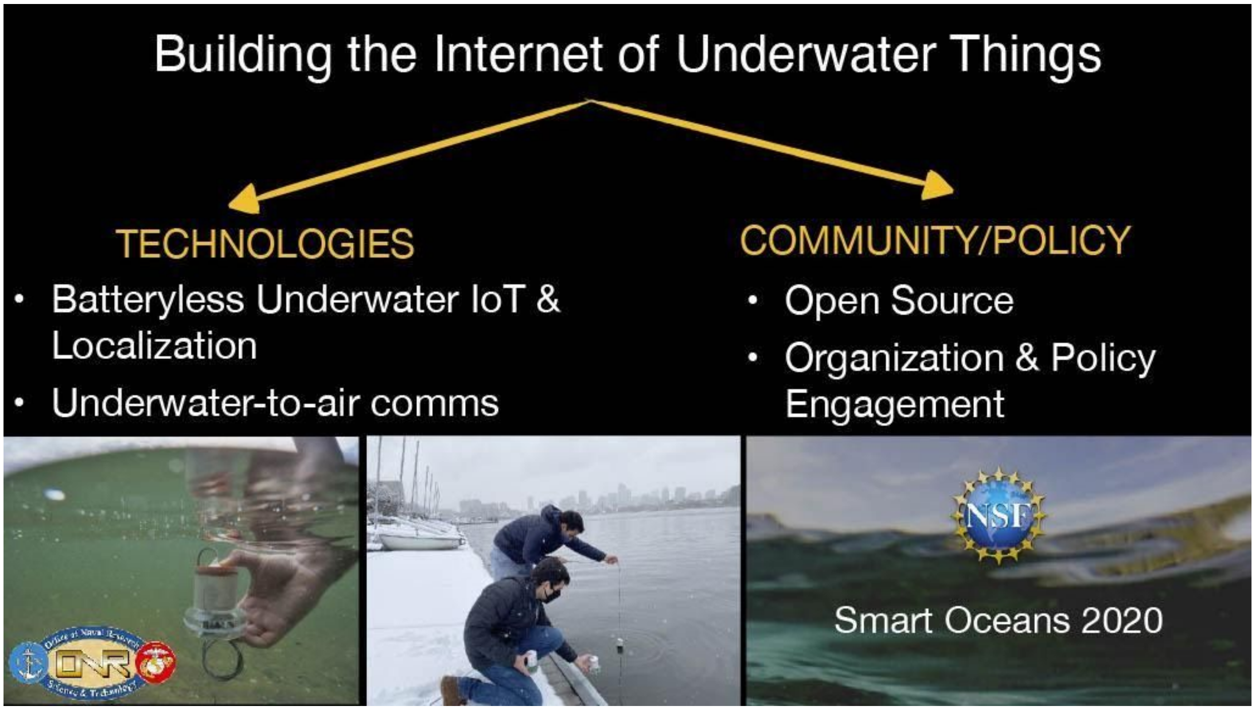

Technology that Enables Compact Sensors to Wirelessly Communicate Across the Water-Air Boundary
Published in: ACM SIGCOMM'18


Technology that Enables Compact Sensors to Wirelessly Communicate Across the Water-Air Boundary
RADAR
Measure Surface Vibration
Surface Vibration
Acoustic
Underwater speaker


Translational Acoustic RF Communication (TARF)
RADAR
Surface Vibration
Acoustic
Introduced algorithms to deal with interference from naturally occurring waves & achieve optimal throughput




Evaluation in Different (Controlled) Environments
Water Tank
Swimming Pool
Swimming Pool with swimmers
RADAR
RADAR
Our technology can communicate (100s of bps) even in the presence of natural surface waves that are 1,000x larger than the acoustic vibrations


Building the Internet of Underwater Things
TECHNOLOGIES
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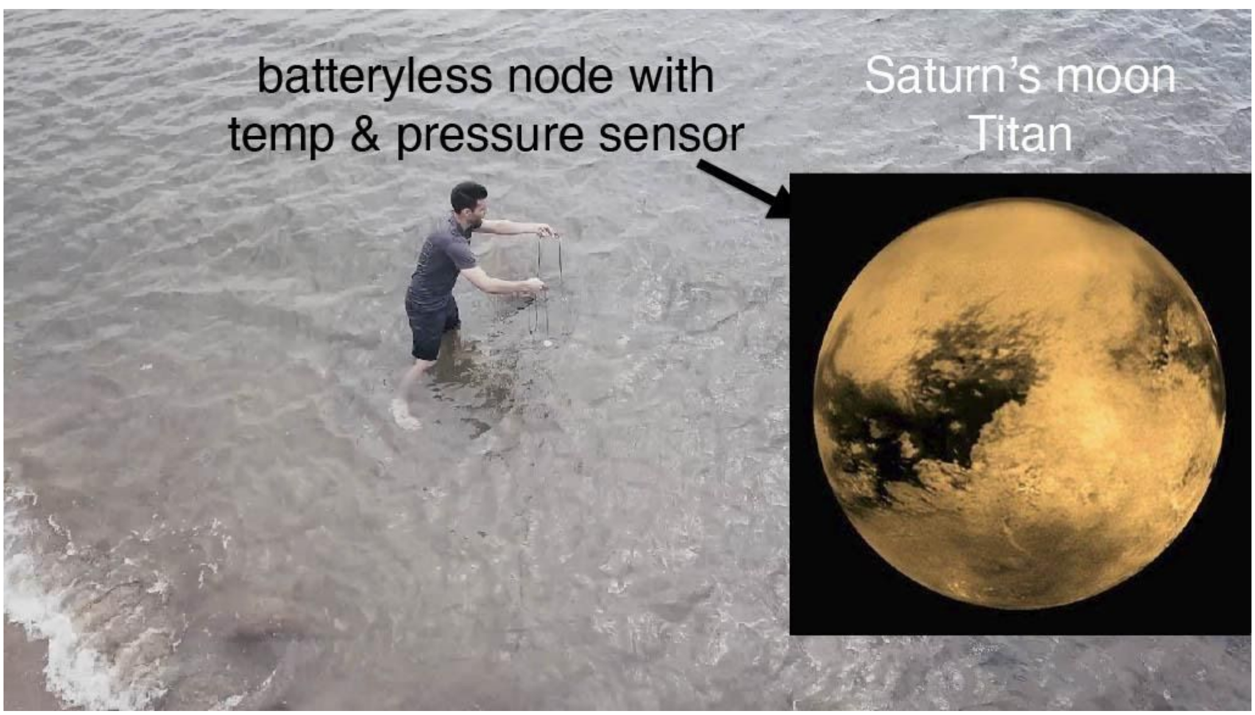
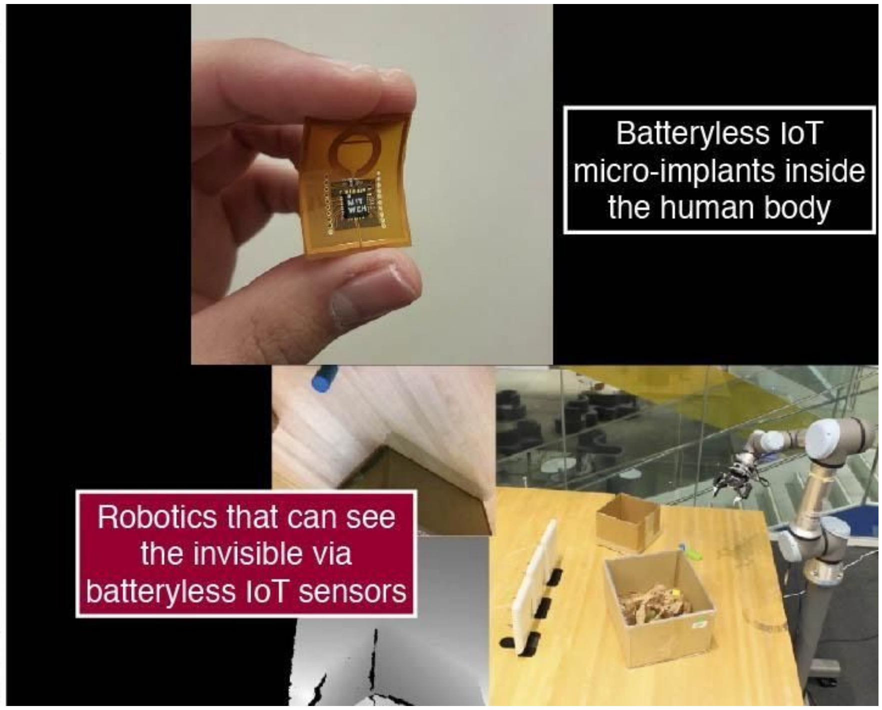
• Underwater-to-air comms
COMMUNITY/POLICY
• Open Source
• Organization & Policy Engagement
NSF
Smart Oceans 2020


NSF
Smart Oceans 2020
Oct. 5-9, 2020
Convergence Accelerator
use-inspired and goal-oriented
1,056 registered & 400+ Institutions
Convergence Accelerator could help to meet "An Ocean of Need"
Innovative NSF program aims to address major ocean-related societal issues
By Randy Showstack | November 19, 2020
Use-inspired
vs
curiosity-driven
http://www.mit.edu/~fadel/papers/Executive_Summary_Ocean_IoT.pdf


The National Academies of SCIENCES ENGINEERING MEDICINE
Ocean Decade U.S.
50+ state senators & legislators
Batteryless Ocean IoT selected as "ocean-shot"
FCC


batteryless node with temp & pressure sensor
Saturn's moon Titan


The Economist
Menu
Science & technology
Oct 17th 2020 edition ›
Good vibrations
How to send underwater messages without batteries
A new device extracts energy from ambient noise
Oct 17th 2020


Batteryless IoT micro-implants inside the human body
Robotics that can see the invisible via batteryless IoT sensors

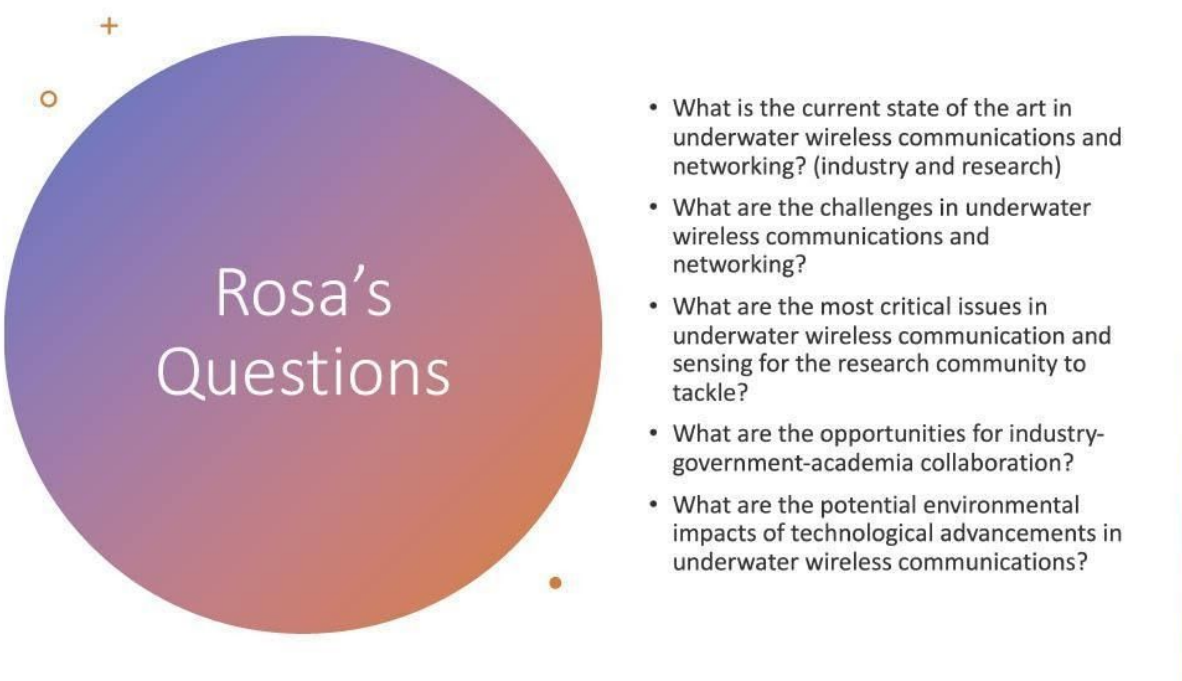

Mario Coumet
Haris Bricic
Waleed Akbar
Andrew McCall
Joshua Craig Anderson
Osvy Rodriguez
Monica Liu
Tara Boroushaki
Sayed Saad Afzal
Holly Birns
Isaac Perper
Mohamed Radwan Abdelhamid


Building the Internet of Underwater Things
Smart Oceans 2020
@fadeladib
@signalkinetics

Session 3 Keynote Speech

"Underwater Communications, Signal Processing, and Networking"

-- Milica Stojanovic (Northeastern University)



IEEE JOURNAL OF OCEANIC ENGINEERING, VOL. 44, NO. 1, JANUARY 2019

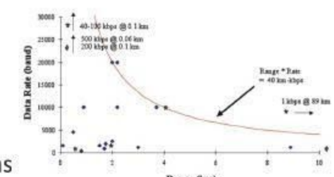
Editorial
Underwater Acoustic Communications: Where We Stand and What Is Next?

I. Introduction

UNDERWATER acoustic communications and networking technologies are critical tools for underwater exploration, subsea resource extraction, national defense missions, etc. Their roles are becoming ever more important as nations around the globe turn to the oceans as sustainable sources of food and energy.

ter modems into networks of fixed and mobile nodes. This push in turn drives the need for higher layer networking technology including medium access control, localization, route discovery, and reliable multihop communications. The last decade has seen significant growth and interest in underwater network stacks and simulators [items 9)–11) in the Appendix], networking protocols, and at-sea network testbeds [item 12) in the Appendix].

What is the current state-of-the-art?



- Operational:
  - acoustic modems
  - networked deployments
  - emerging standards
- Development:
  - software-defined platforms
- Research:
  - channel modeling
  - signal processing for reliable acoustic communications
  - network integration: sensing, mobility, data fusion

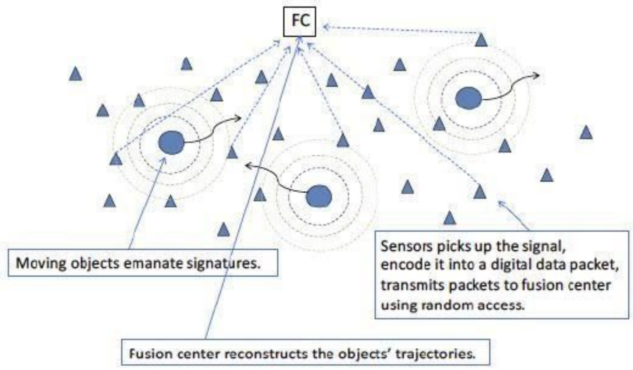
What are the challenges?

- Market & need for specific, well-defined applications
- Gap between research and implementation
- Establishment of common frameworks:
  - software-defined acoustic modems & networks
  - data-bases for typical channel & traffic models

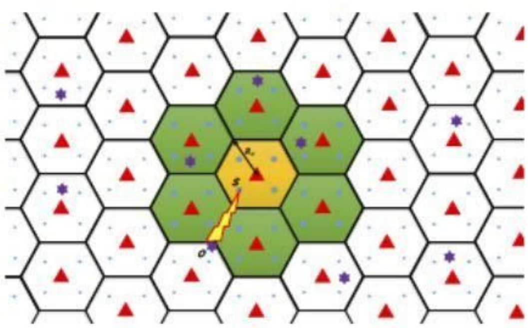
What are the most critical issues for the research community?

- Channel modeling (still)
- Signal processing: tx-rx feedback
  - predictable vs. unpredictable channel effects
  - power and rate control
  - transmit beamforming (and MIMO)
  - adaptive modulation (spectrum shaping)
- Networks:
  - cellular / peer-to-peer (and hybrid)
  - deterministic / random access (and hybrid)
  - spatial reuse and efficient resource allocation
  - mobility and topology control
  - sensor integration and data fusion
  - standardization of network architectures (layers)

Example: Object tracking in a sensor network



Top-level design for scalability: Zoning



- Pattern is repeated across arbitrary area with no increase in processing complexity at the FC.
- Total power scales linearly with number of cells.
- Tracking algorithm employed by the FC remains the same regardless of the area size.
- Each cell acts as both the central cell of its DU, and as a helping neighbor.
- Procedure carried out within one cell is the same for all cells.
- Entrance/departure issue is automatically solved.

[M.Alimadadi, M.Stojanovic and P.Closas, "Object Tracking in Random-access Sensor Networks: A Large-scale Design," IEEE Internet of Things Journal, April 2020.]

- A sensing cell and its nearest neighbors form a design unit (DU).
- Each sensing cell has a fusion center (FC).
- Sensors in one cell report to that cell's FC.
- Each FC runs an extended Kalman filter tuned to M objects, enough for a DU.
- Objects outside of the DU are not picked by the central cell's sensors.
- At the end of each collection interval, FCs within a DU exchange information; data fusion is performed.
- Data fusion includes overwriting, provisions for delay.

Top-level design for scalability: Zoning

- Pattern is repeated across arbitrary area with no increase in processing complexity at the FC.
- Total power scales linearly with number of cells.
- Tracking algorithm employed by the FC remains the same regardless of the area size.
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- Objects outside of the DU are not picked by the central cell's sensors.
- At the end of each collection interval, FCs within a DU exchange informa… data fusion is performed.
- Data fusion includes overwriting, provisions for delay.

Is this useful? Is there an application?
Does it stand a chance of being fielded?

What are the opportunities and approaches for industry-government-academia collaboration?

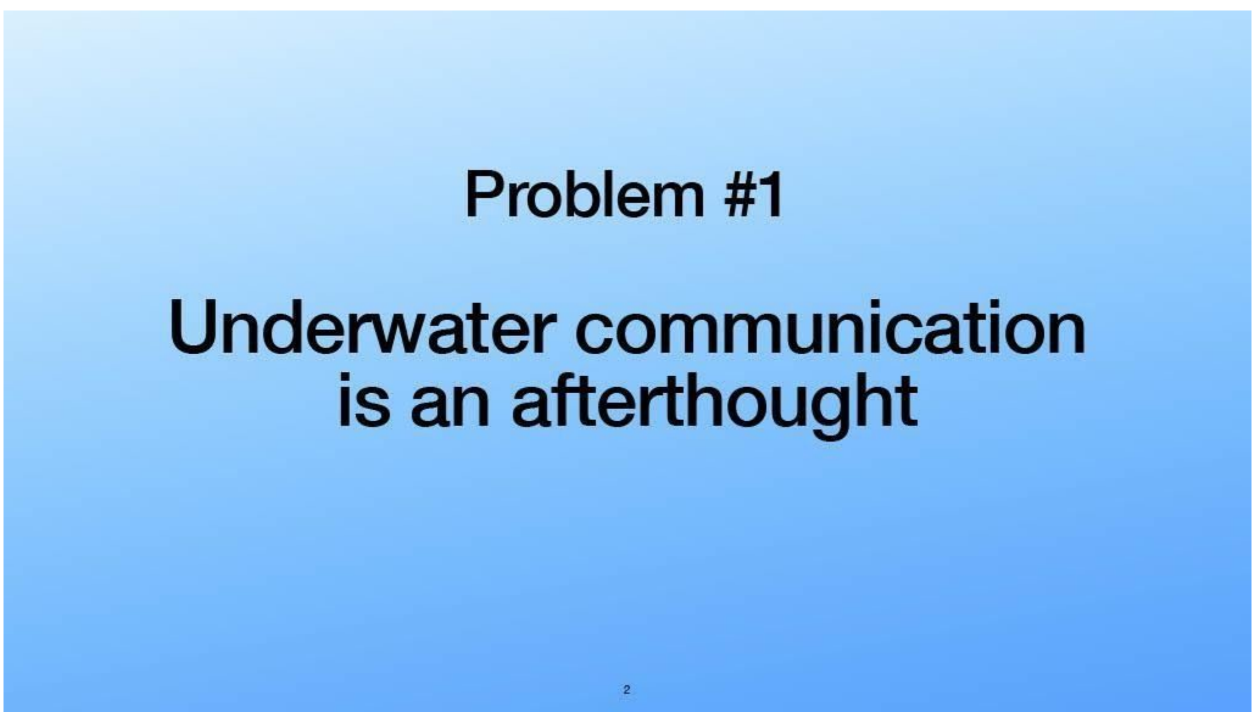
- Identify specific applications and underlying engineering problems:
  - immediate (e.g. monitoring in offshore tanks)
  - near-future (e.g. glider networks)
  - far-future (e.g. global underwater coverage)
- Identify partnerships (multi-level, multi-disciplinary) and form teams
- Ensure efficient technology transfer to close the research-implementation gap


What are the potential environmental impacts?

Session 4 Keynote Speech

"Underwater Communication for Marine Robotics"

-- Mandar Chitre (NUS Singapore)



Solutions

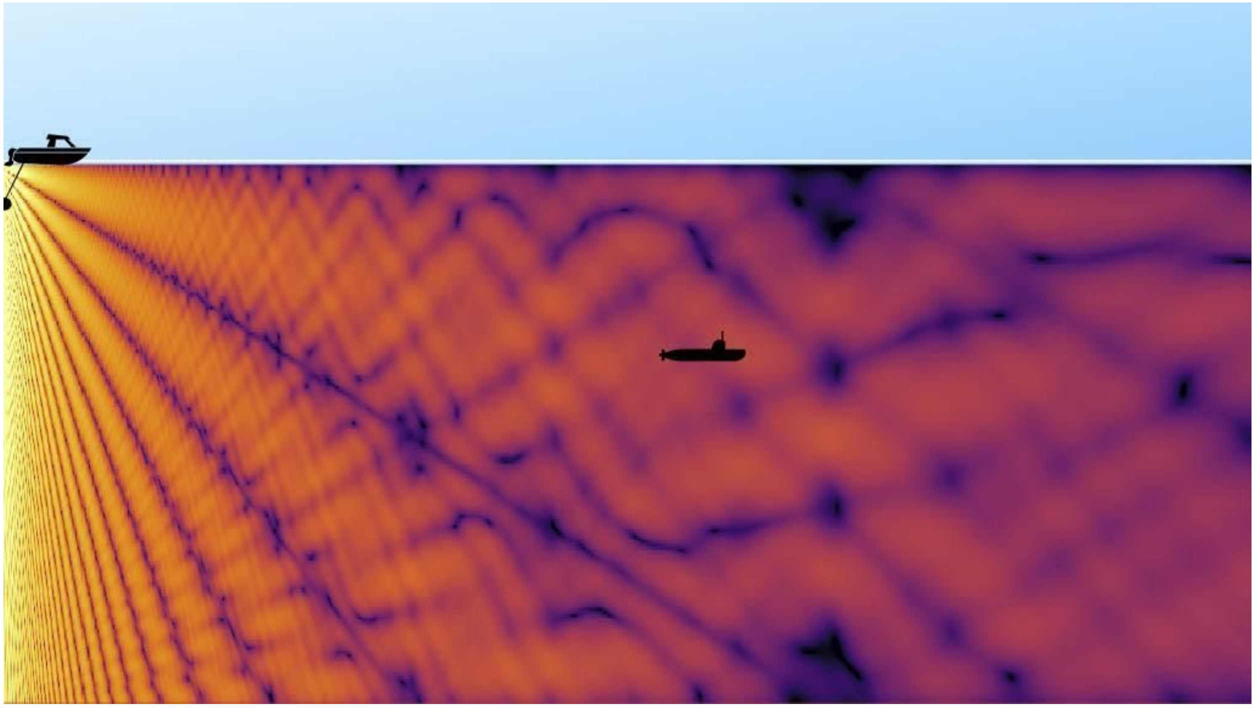
Existing work & new areas of research

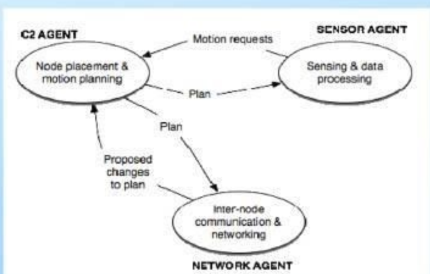
- Systems thinking for IoUT
- Acoustic considerations in AUV design
- Techniques & technologies:
  - Spatial diversity
  - Multi-band / multi-modal communication
  - Distributed spatial diversity / cooperative communications

Problem #2

Underwater acoustic propagation is poorly understood

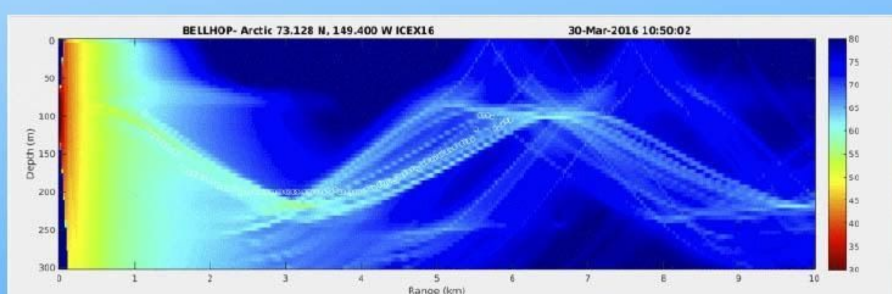
4





AUV mission planning with communication constraints

M. Chitre, "A holistic approach to underwater sensor network design," in Proceedings of Naval Technology Seminar (NTS) 2011, (Changi Exhibition Centre, Singapore), May 2011.



H. Schmidt & T. Schneider, "Acoustic communication and navigation in the new Arctic — A model case for environmental adaptation," in UComms'16, Italy, 2016.

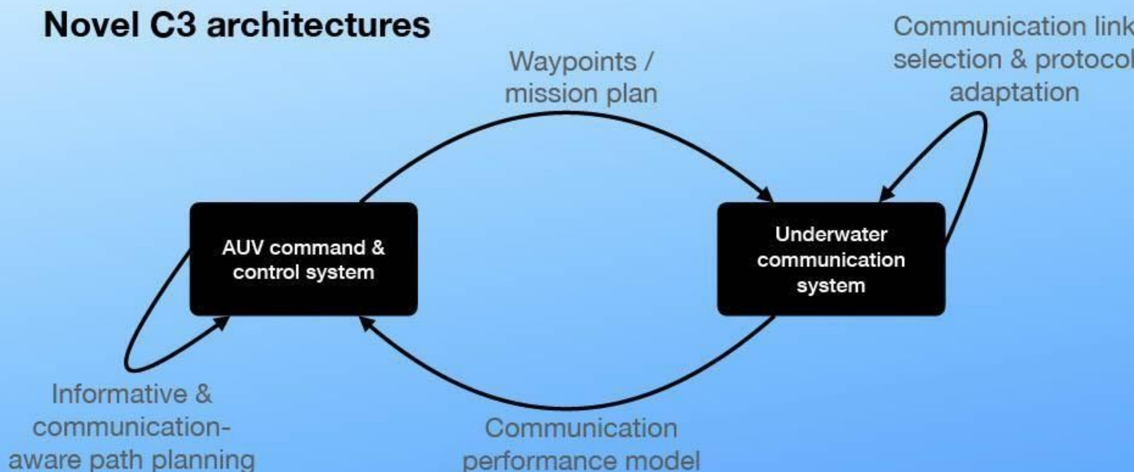
Solutions

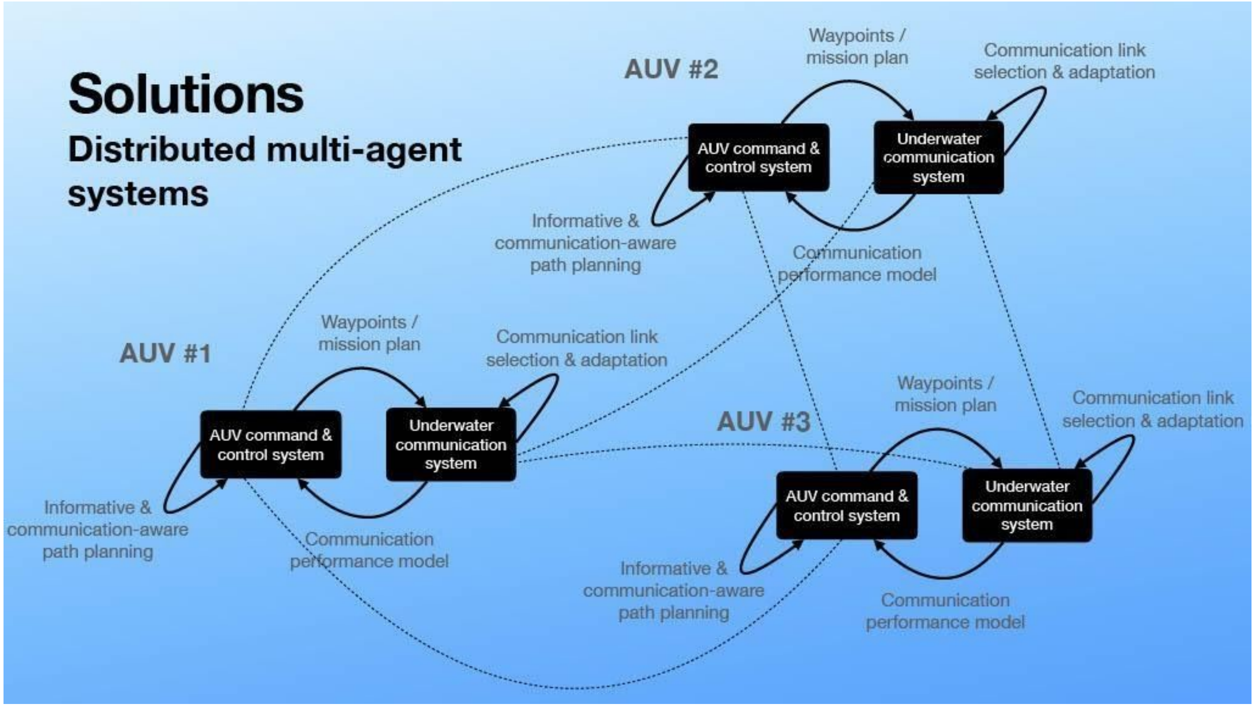
Areas of research

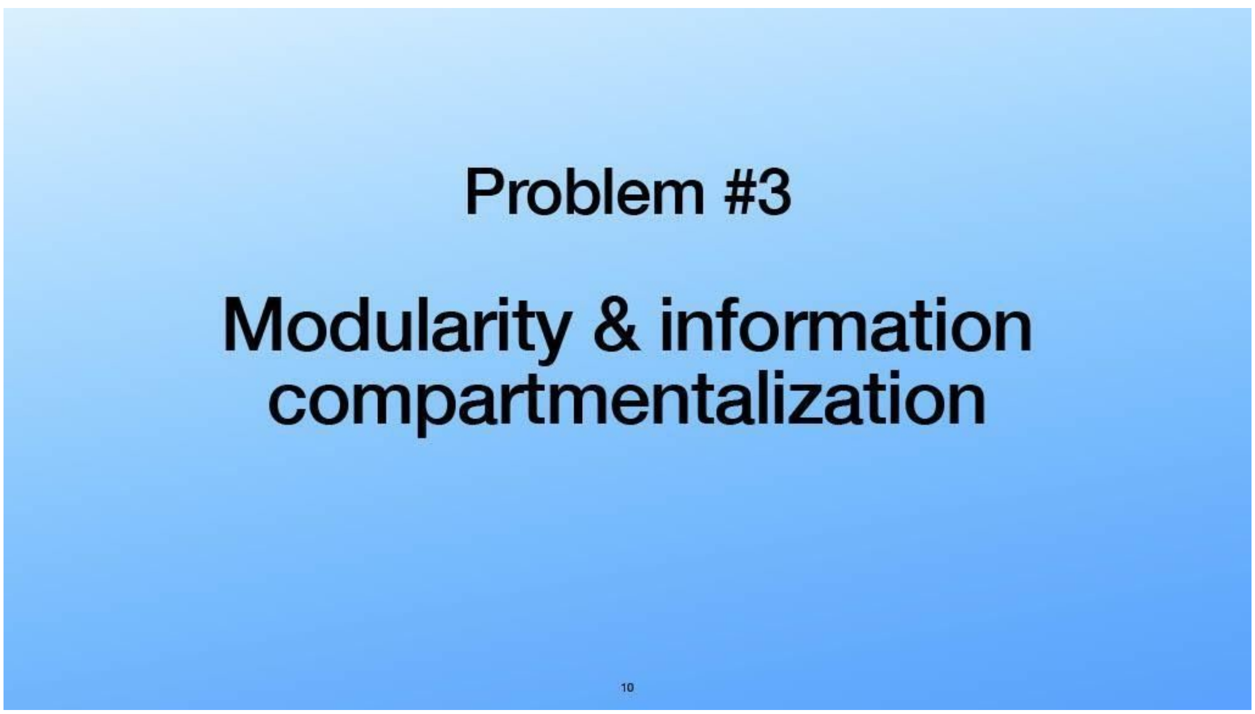
- Path-planning with acoustic constraints
- Low-complexity acoustic propagation models onboard AUVs
  - SciML: PINNs
- Rapid environmental assessment
- Online environmental estimation & modeling
  - Differentiable propagation modeling
  - Informative path planning

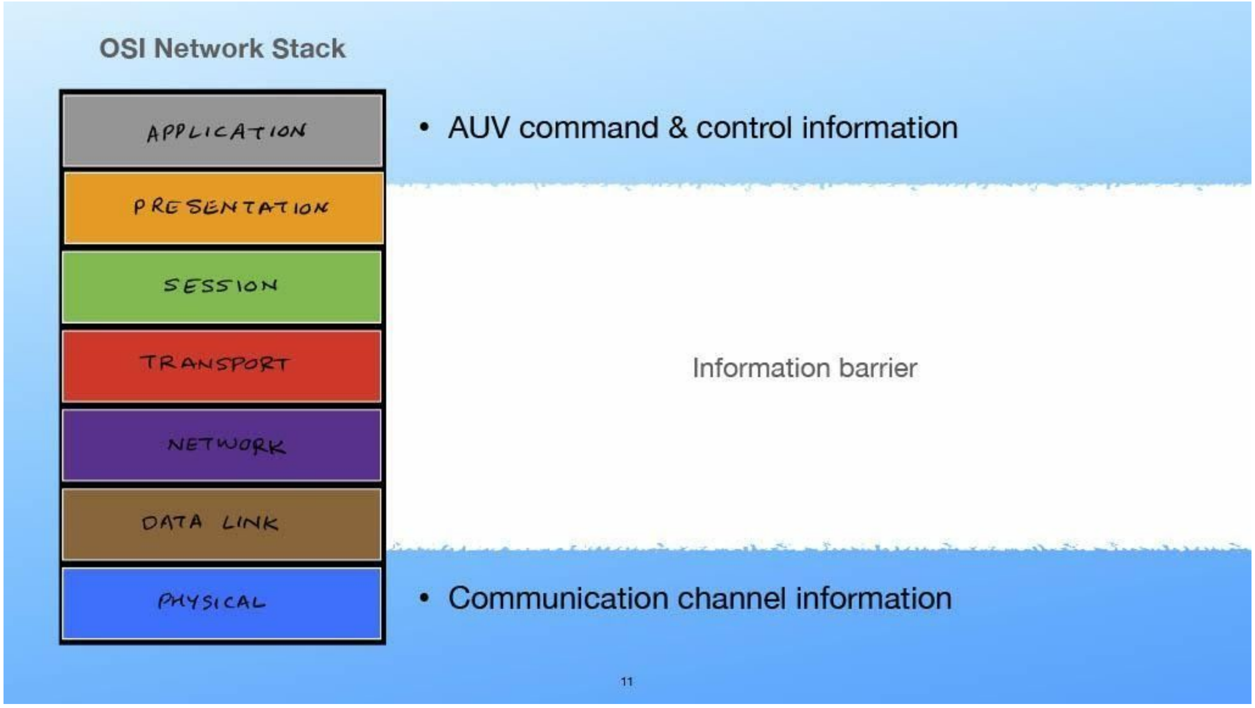
Solutions

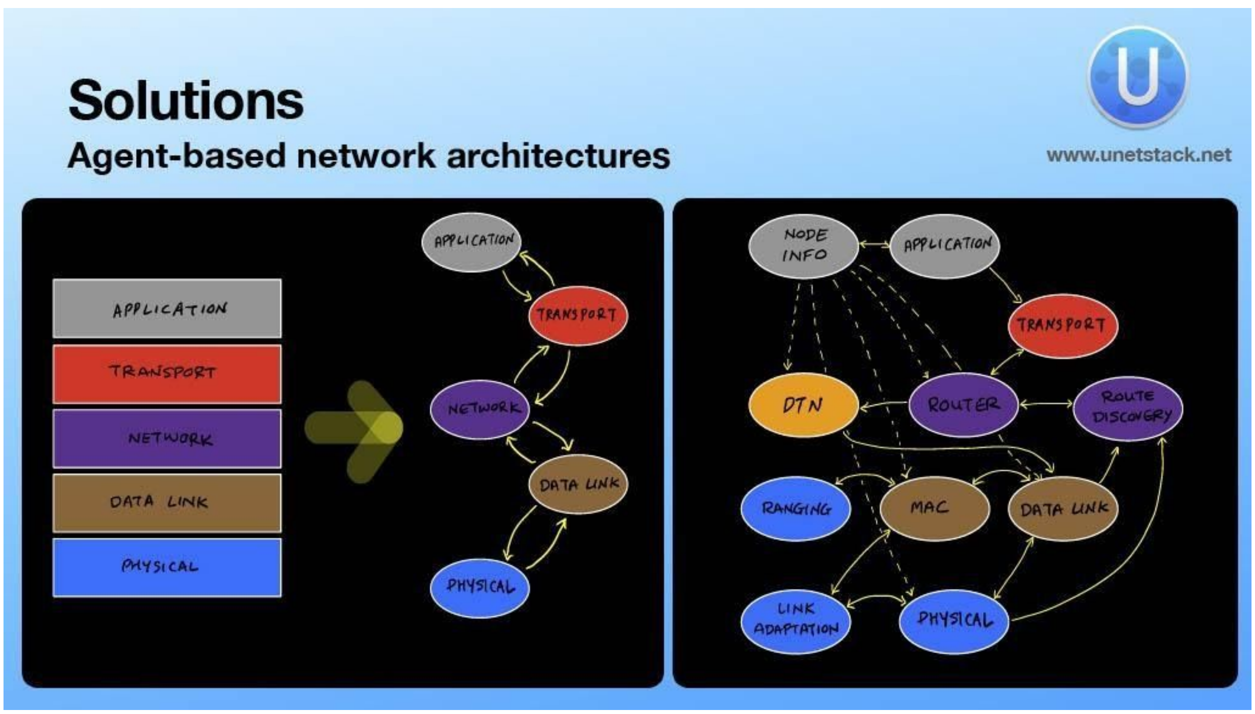
Novel C3 architectures




Solutions
Distributed multi-agent systems
AUV #1
AUV #2
AUV #3
AUV command & control system
Underwater communication system
Waypoints / mission plan
Communication link selection & adaptation
Informative & communication-aware path planning
Communication performance model
AUV command & control system
Underwater communication system
Waypoints / mission plan
Communication link selection & adaptation
Informative & communication-aware path planning
Communication performance model
AUV command & control system
Underwater communication system
Waypoints / mission plan
Communication link selection & adaptation
Informative & communication-aware path planning
Communication performance model

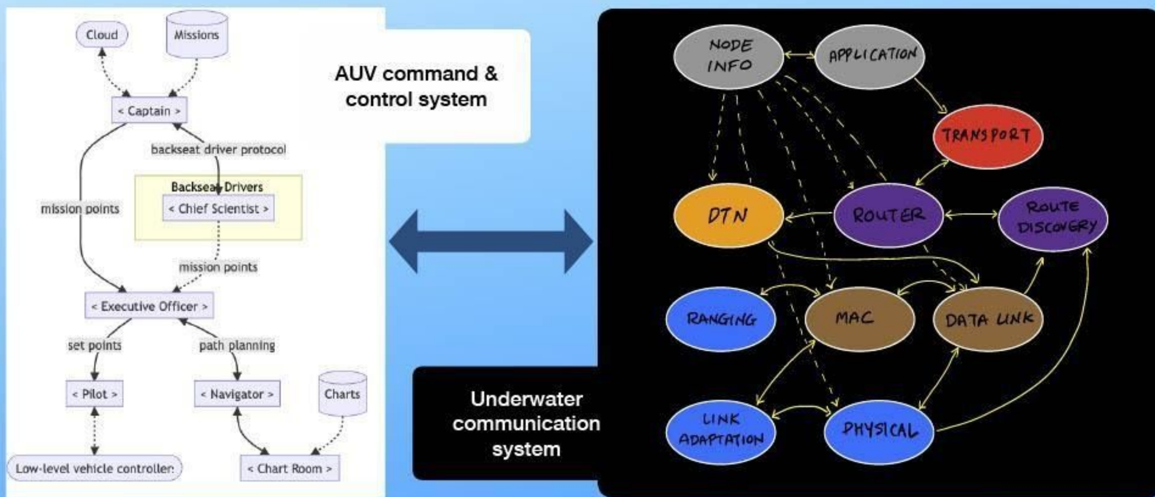

Problem #3
Modularity & information compartmentalization
10


OSI Network Stack
APPLICATION
PRESENTATION
SESSION
TRANSPORT
NETWORK
DATA LINK
PHYSICAL
• AUV command & control information
Information barrier
• Communication channel information
11


Solutions
Agent-based network architectures
www.unetstack.net
APPLICATION
TRANSPORT
NETWORK
DATA LINK
PHYSICAL
APPLICATION
TRANSPORT
NETWORK
DATA LINK
PHYSICAL
NODE INFO
APPLICATION
TRANSPORT
DTN
ROUTER
ROUTE DISCOVERY
RANGING
MAC
DATA LINK
LINK ADAPTATION
PHYSICAL

Solutions

Agent-based command & control systems



Take aways

- Solving the “underwater communications problem” requires a holistic systems approach that spans many areas of research:
  - AUV design
  - Communication theory
  - Propagation modeling
  - Machine learning
  - Agent-based architectures
  - Distributed decision-making

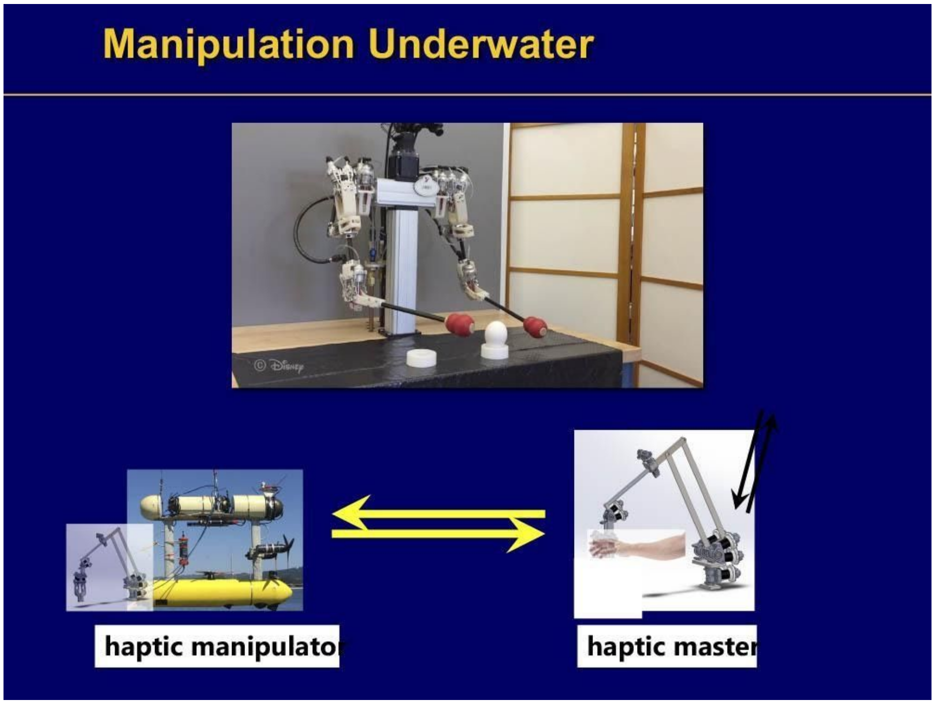
“Most unsolved problems today lie on boundaries across domains”

Discussion

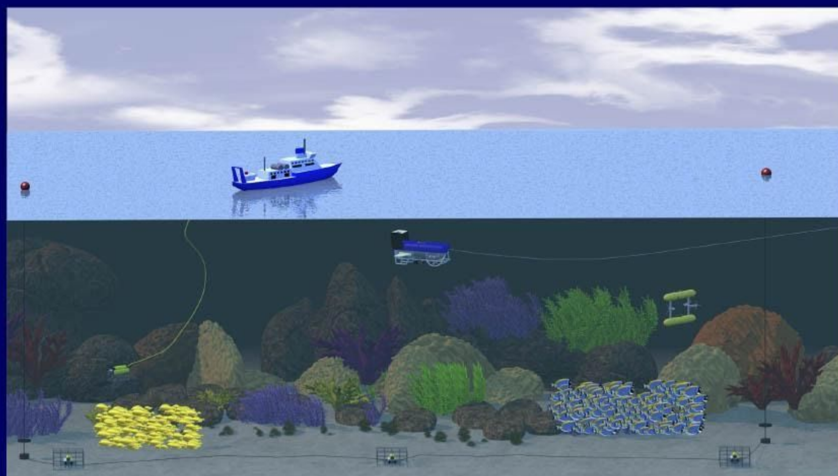
Appendix C. Slides of Short Talks

Session 1 Short Talk

"Looking forward - Marine Robotics and High Resolution Mapping in the Ocean"
-- Hanumant Singh (Northeastern University)



Can we completely Transition to Fisheries Independent Stock Assessment?



Machine Learning for Marine Applications

The New York Times

SCIENCE

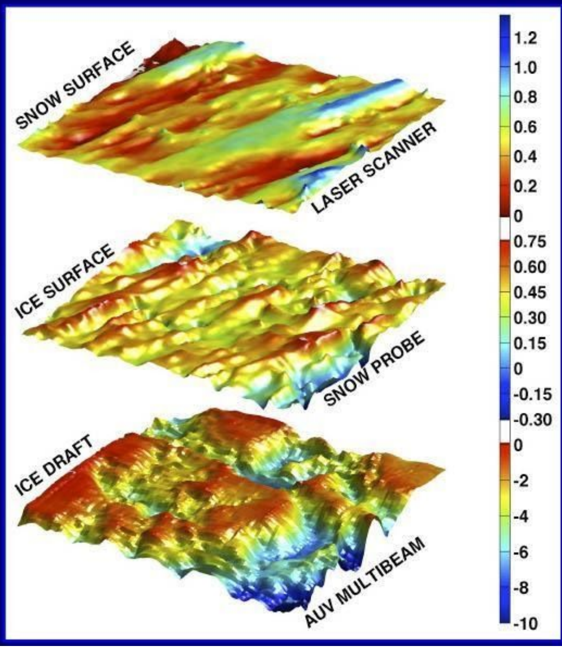
A Supercolony of Penguins Has Been Found Near Antarctica

Satellite images and a drone discovered about 1.5 million Adélie penguins living in the Danger Islands, one of two species whose habitats require ice.

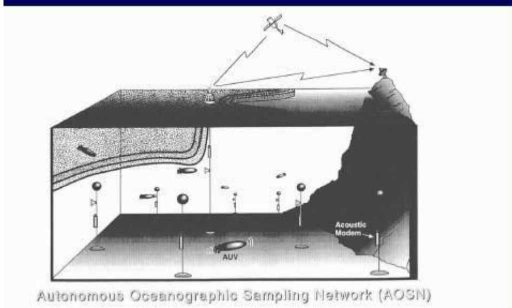
Data poor -> Data Rich
Data Rich but Information Poor

Successes
Penguin Counting
Automated Analysis for Scallops

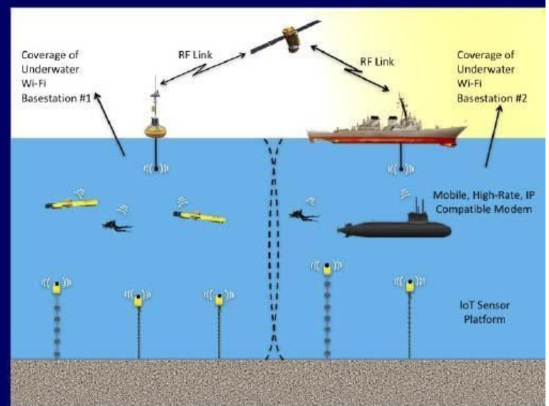
2012 Sipex II Expedition with AAD



Spatial and Temporal Mapping



Autonomous Ocean Sampling Networks (1993)



Seanet – The internet of underwater things (Courtesy T Melodia et al)

Session 1 Short Talk

"Summary of 2018 NSF Seafloor Sensing Workshop and Recommendations"
-- Christopher Parrish(Oregon State University)

Summary of 2018 NSF Seafloor Sensing Workshop & Recommendations

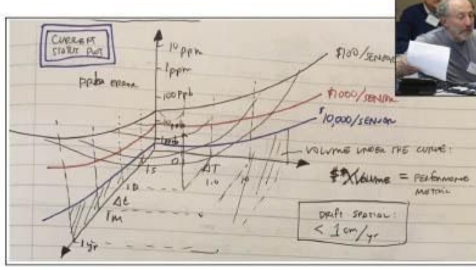
Christopher Parrish
NSF workshop BLUE-UCI2021
January 12, 2021

Oregon State University

NSF

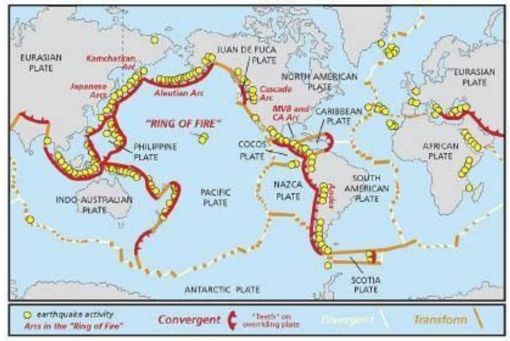
2018 Workshop

- **Integrating Science Needs with Advanced Seafloor Sensor Engineering to Provide Early Warning of Geohazards**: *Visioning Workshop and Roadmap for the Future*
  - Supported by the National Science Foundation (NSF), OCE Division of Ocean Sciences (Award # 1817257)
  - July 12-13, 2018 in Gleneden Beach, OR
  - 64 participants, representing 34 different organizations
    - Academia, government, and industry



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



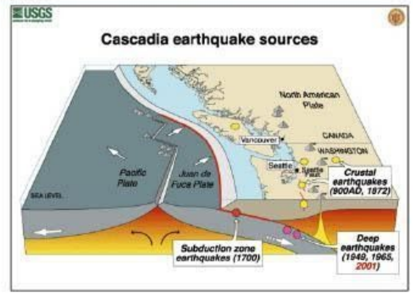


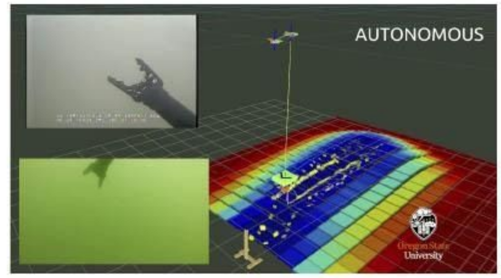
Figure credits: top: National Parks Service; bottom: USGS

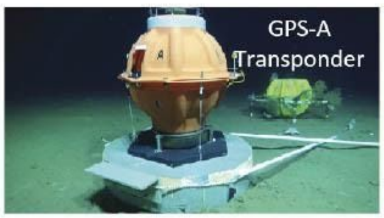
Emphasis on Requirements for Early Warning Systems

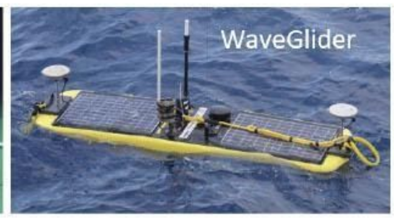
Requirements	EEW	TEW
Sensor type (sample rate)	Strong motion (100Hz) Broadband (100Hz) Strain (≥ 1Hz) Acoustic GPS (>1Hz) Absolute pressure (≥ 1Hz) Hydrophones? (1kHz?)	Generally the same as for EEW, but with less stringent constraints on data latency, etc.
Latency (includes packet size)	<2s	<30s
Sensor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

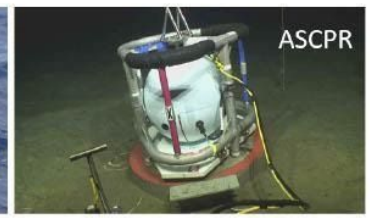
Current State-of-the-Art



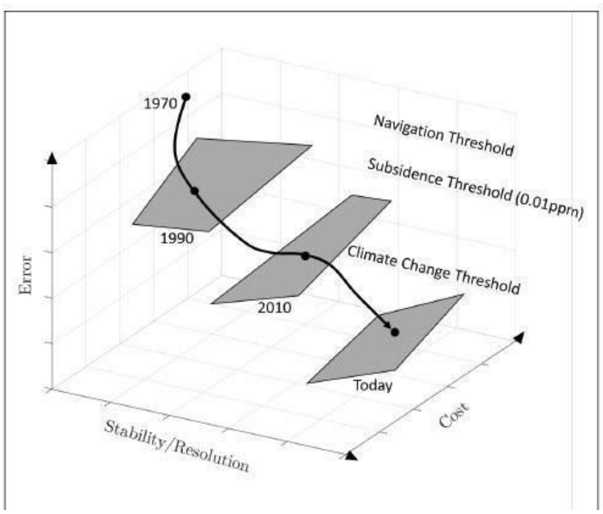


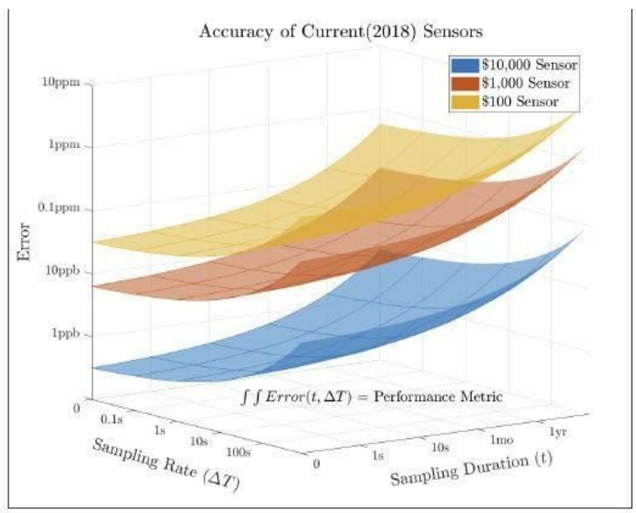






Evolution of Sensing Technology

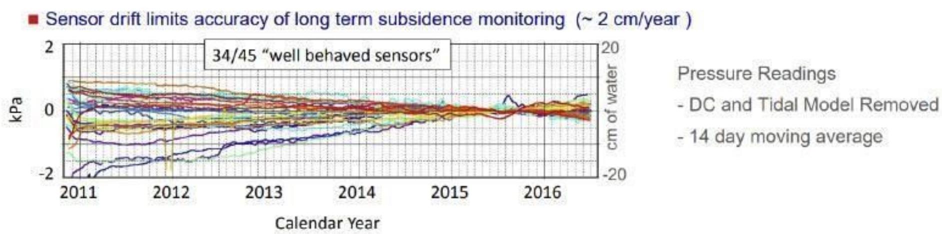




Sensor Needs and Technology Gaps

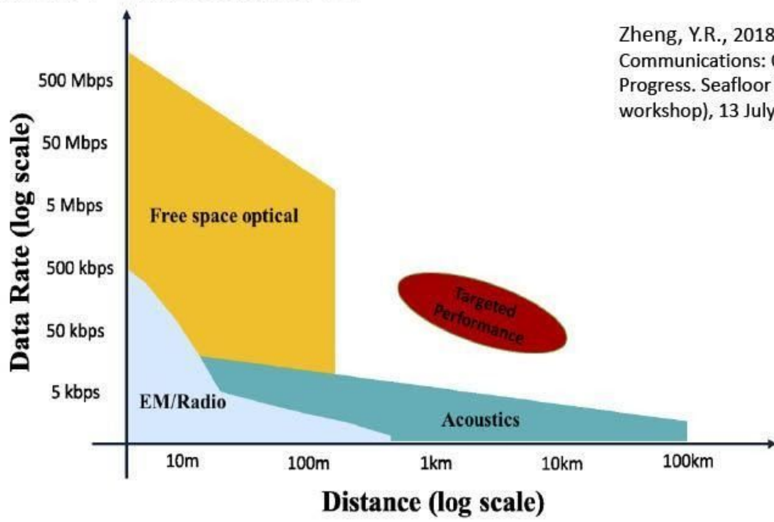
1. Spatial coverage
2. Measurement uncertainty
3. Rapid deployment
4. Cost-effectiveness of seafloor sensors
5. Environmental impacts

Calibration and drift



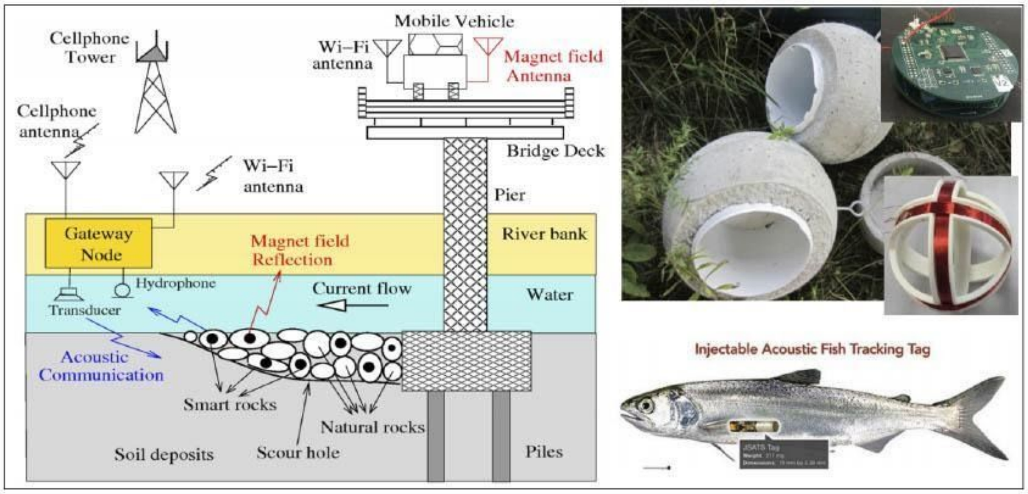
Limitations of Current Underwater Communications & Desired Performance

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



Internet of Underwater Things (IoUT)

To be continued in current workshop: *BLUE UCI 2021*



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

Environmental impacts of seafloor sensors

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

Actionable Strategies/Recommendations

- Establish a **seafloor sensing consortium** or **virtual center**, dedicated to training, facilitating communication, and collaboration opportunities
  - Ex: RCN on seafloor sensing
  - Coordinate conferences and workshops and special issues
  - Maintain database of loanable equip
- *Further R&D to address unmet challenges in:*
  - *Power harvesting*
  - *Decreased power consumption*
  - *Communications*
  - *Timing*
  - *Interoperability*
  - *Sensor drift and calibration*
  - *Long-duration autonomy*
  - *Modular and reconfigurable sensors/network*

More information

2018 Workshop Report:
https://ir.library.oregonstate.edu/concern/technical_reports/dv140069q

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

Contact Info:

Christopher.Parrish@oregonstate.edu

Session 1 Short Talk

"The JANUS Underwater Communication Standard"
-- Joao Alves, CMRE Italy

NATO OTAN — SCIENCE AND TECHNOLOGY ORGANIZATION
CENTRE FOR MARITIME RESEARCH AND EXPERIMENTATION — S&T organization CMRE

THE JANUS UNDERWATER COMMUNICATIONS STANDARD

João Alves
Principal Scientist / Project Leader at the NATO Centre for Maritime Research and Experimentation

NSF Workshop Jan12-14, 2021 — Slide 1

NATO OTAN — SCIENCE AND TECHNOLOGY ORGANIZATION
CENTRE FOR MARITIME RESEARCH AND EXPERIMENTATION — S&T organization CMRE

Underwater Communications: Why ?

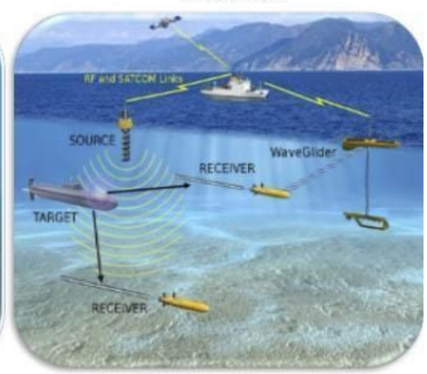
Sensor Networks

Source: unknown

Oil and Gas

Source: IMDEA Networks

Defence



Source: NATO STO CMRE

NSF Workshop Jan12-14, 2021 — Slide 2

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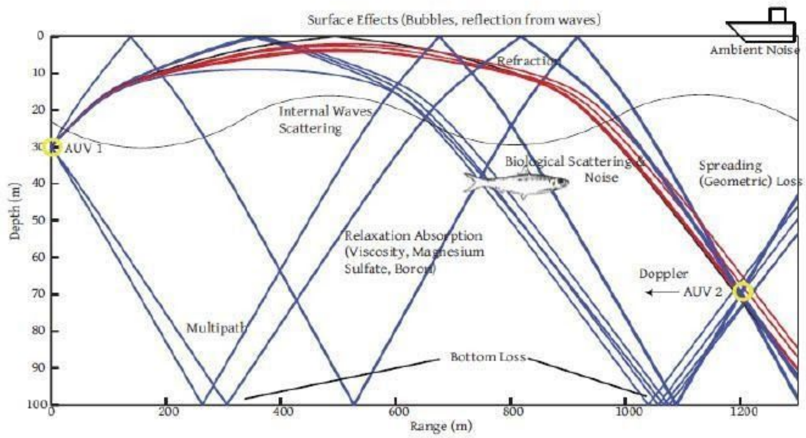
SCIENCE AND TECHNOLOGY ORGANIZATION
CENTRE FOR MARITIME RESEARCH AND EXPERIMENTATION

S&T organization CMRE

Acoustic Underwater Communications



"Advances in Integrating Autonomy with Acoustic Communications for Intelligent Networks of Marine Robots", Toby Schneider, PhD thesis, 2013

NSF Workshop Jan12-14, 2021 Slide 3

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CENTRE FOR MARITIME RESEARCH AND EXPERIMENTATION

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The issue of (lack of) interoperability

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JANUS

SCIENCE AND TECHNOLOGY ORGANIZATION
CENTRE FOR MARITIME RESEARCH AND EXPERIMENTATION

JANUS

The first digital underwater communications standard

- Promulgated March 2017 as **STANAG 4748**
- 10 years of development by CMRE and partners
- It's open and free to use (NATO, non-NATO, Military, Civilian)
- Designed to be simple and robust
- Not intended to replace / override manufacturer's efforts
- Reference implementations in Matlab and C available at:

www.januswiki.org

SCIENCE AND TECHNOLOGY ORGANIZATION
CENTRE FOR MARITIME RESEARCH AND EXPERIMENTATION

Why JANUS is important

- Internet, WiFi etc., all built on standards
- Before JANUS there were no digital underwater communications standards!
- We are moving from a paradigm of few high-value manned assets to many low(er)-value unmanned distributed systems
- Robust and simple implementation
- Possibility to use "hardware of opportunity"

JANUS is not trying to replace existing industrial efforts but rather creating the means for their co-existence

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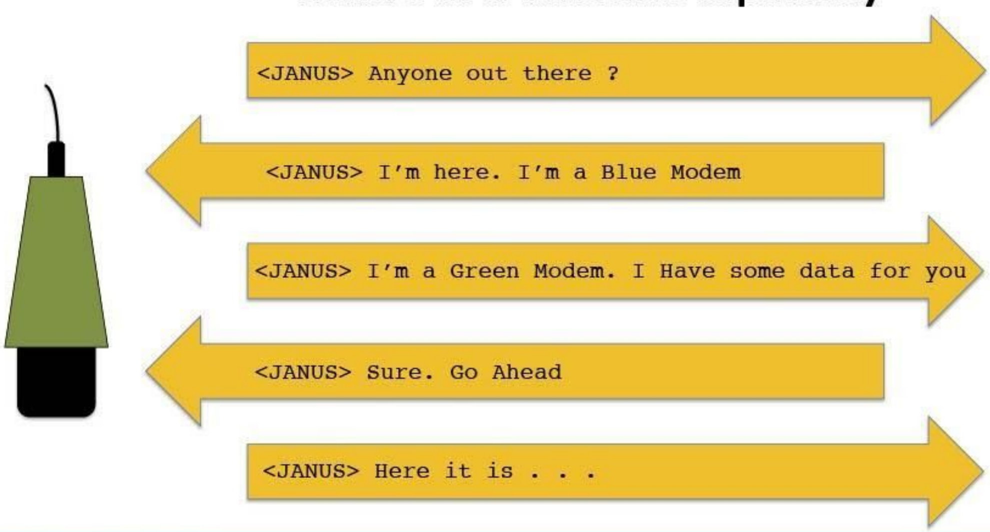
SCIENCE AND TECHNOLOGY ORGANIZATION
CENTRE FOR MARITIME RESEARCH AND EXPERIMENTATION

JANUS as a baseline capability



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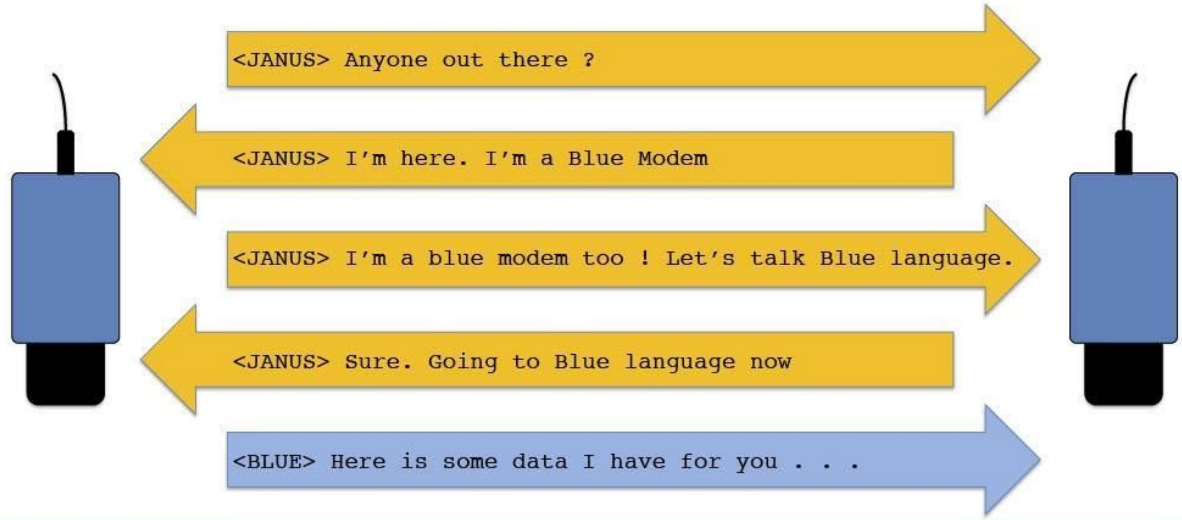
CENTRE FOR MARITIME RESEARCH AND EXPERIMENTATION

JANUS supporting multilingual operation



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CENTRE FOR MARITIME RESEARCH AND EXPERIMENTATION

Takeaways

- Interoperability is fundamental as we expand our presence in the Ocean
- JANUS is an open standard for digital underwater communications
- Several manufacturers offer JANUS-compliant acoustic modems
- JANUS can be used to enable baseline functionalities across different vendors
- JANUS is not trying to replace existing industrial efforts but rather creating the means for their co-existence
- JANUS is a live standard ! Revisions and upgrades are in the pipeline: **A lot of R&D ahead !**
- You can play with JANUS and build your own Transmitter and/or Receiver
- You can try it today by downloading example code (C and Matlab available) from www.januswiki.org

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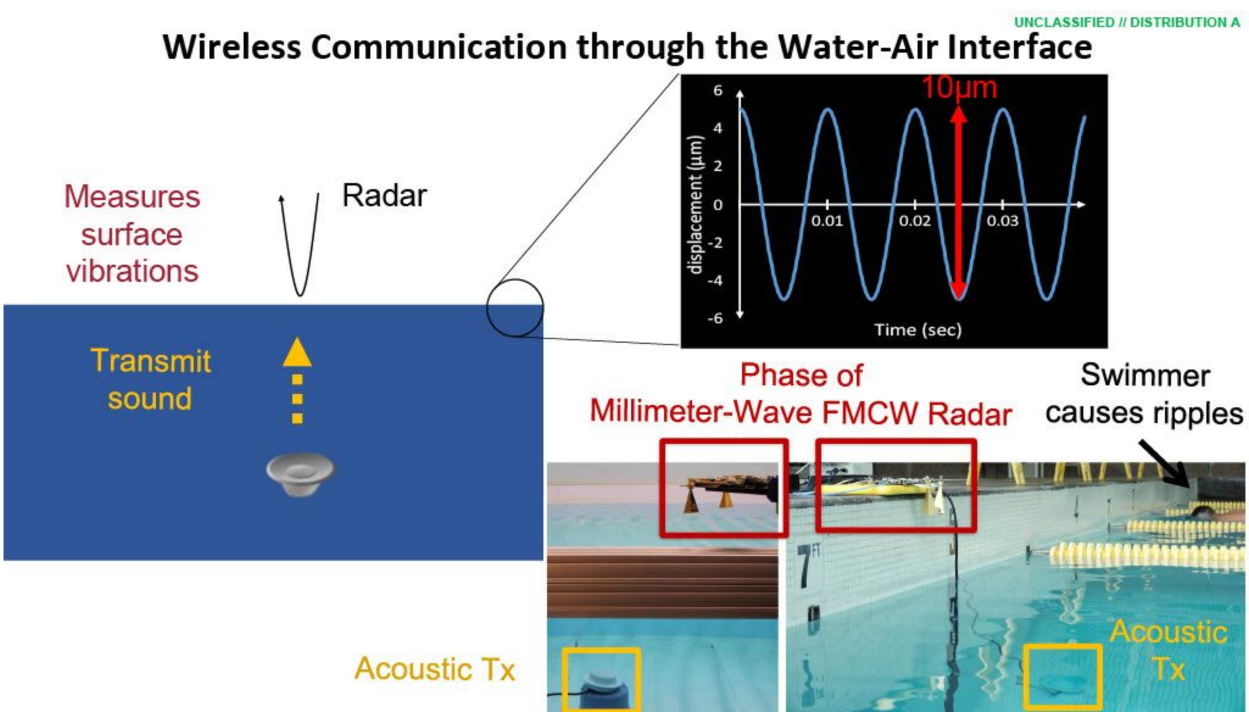
CENTRE FOR MARITIME RESEARCH AND EXPERIMENTATION
S&T organization CMRE
THE JANUS UNDERWATER COMMUNICATIONS STANDARD
João Alves
Principal Scientist / Project Leader at the NATO Centre for Maritime Research and Experimentation
joao.alves@cmre.nato.int
NSF Workshop Jan12-14, 2021
Slide 11

Session 2 Short Talk

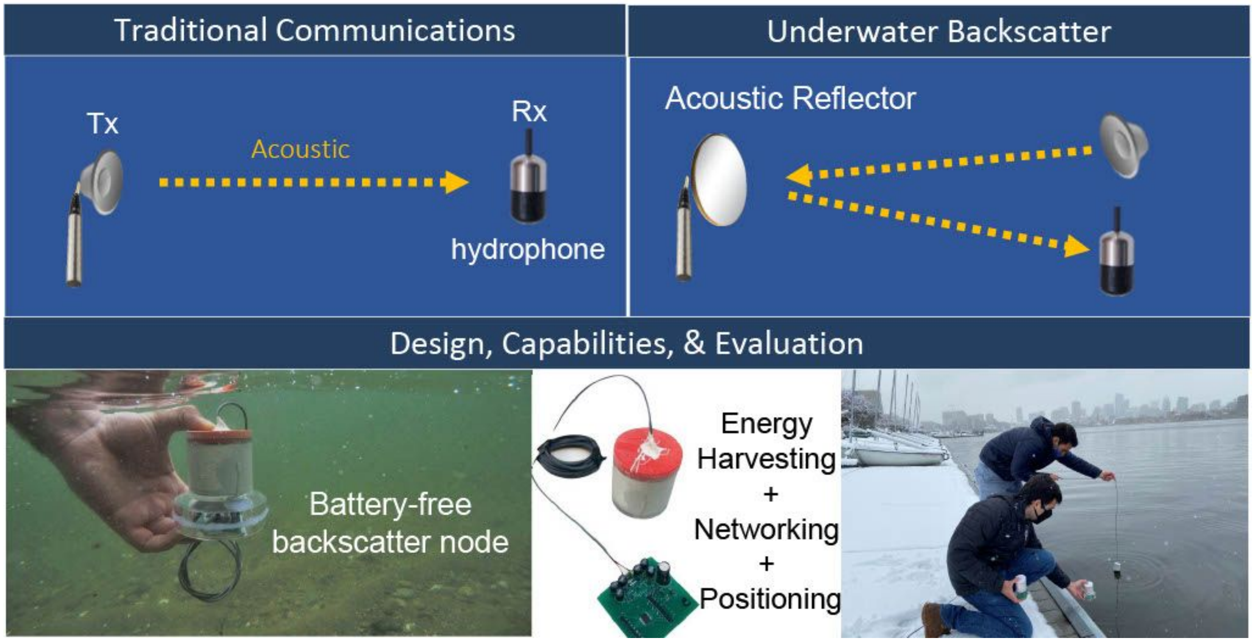
"New Directions in Underwater Communication Electronics"

-- Santanu Das (ONR)



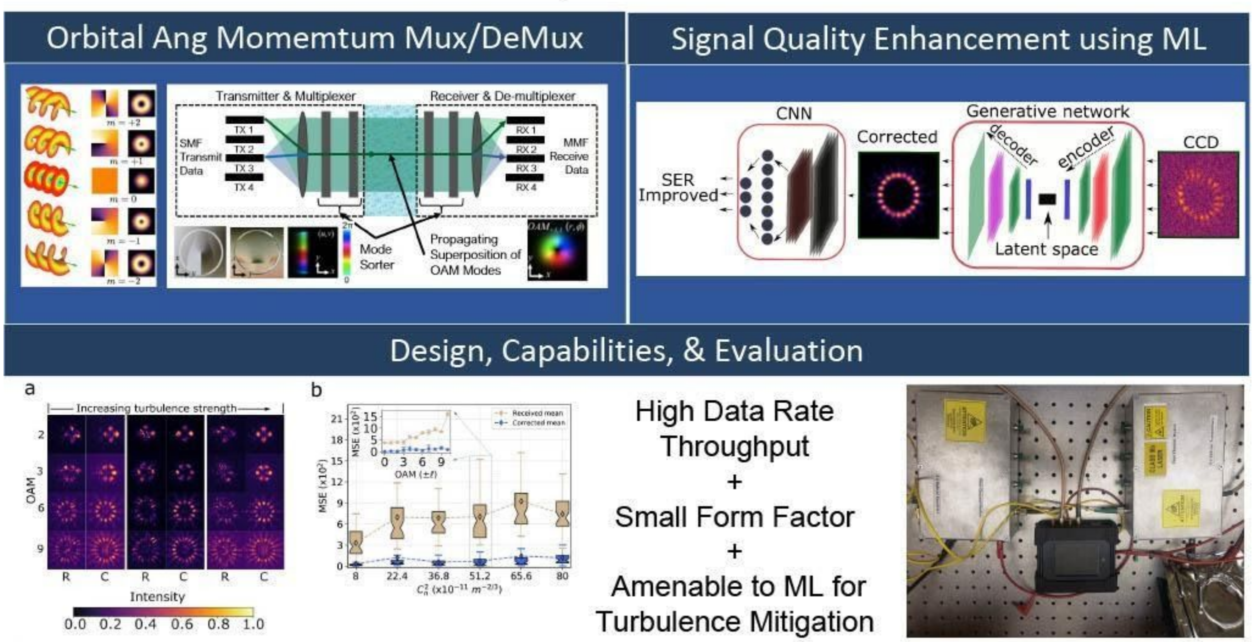
UNCLASSIFIED // DISTRIBUTION A

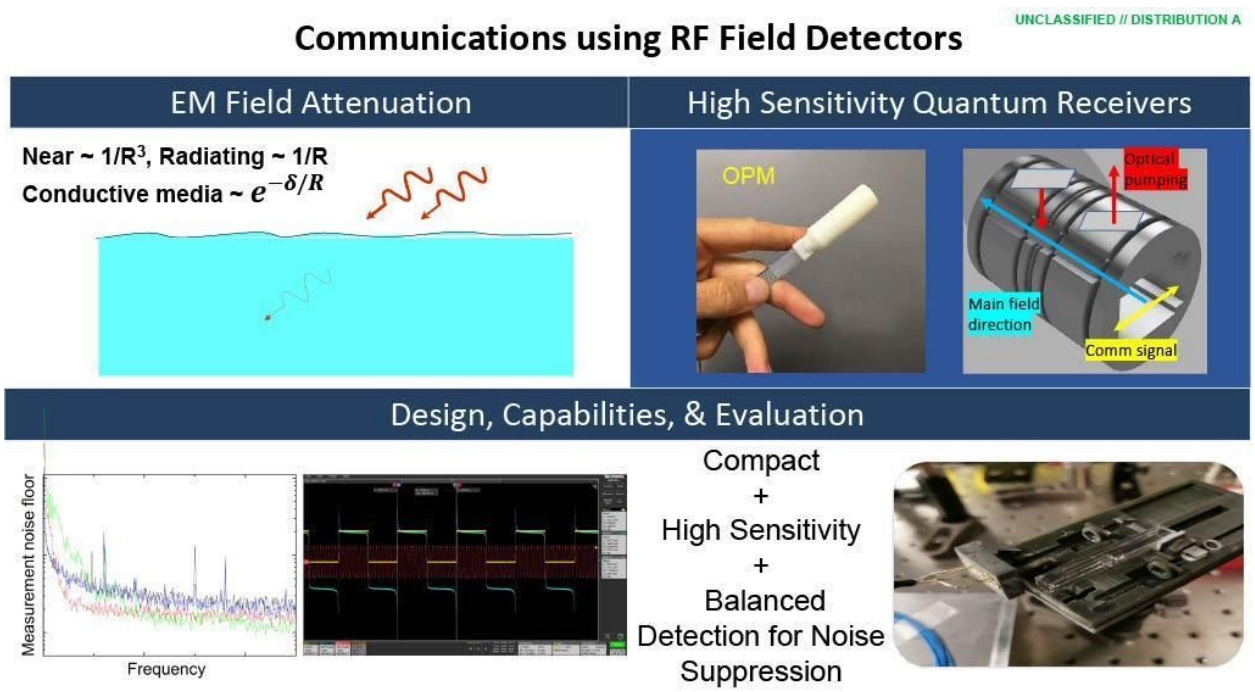
Underwater Backscatter Networking



UNCLASSIFIED // DISTRIBUTION A

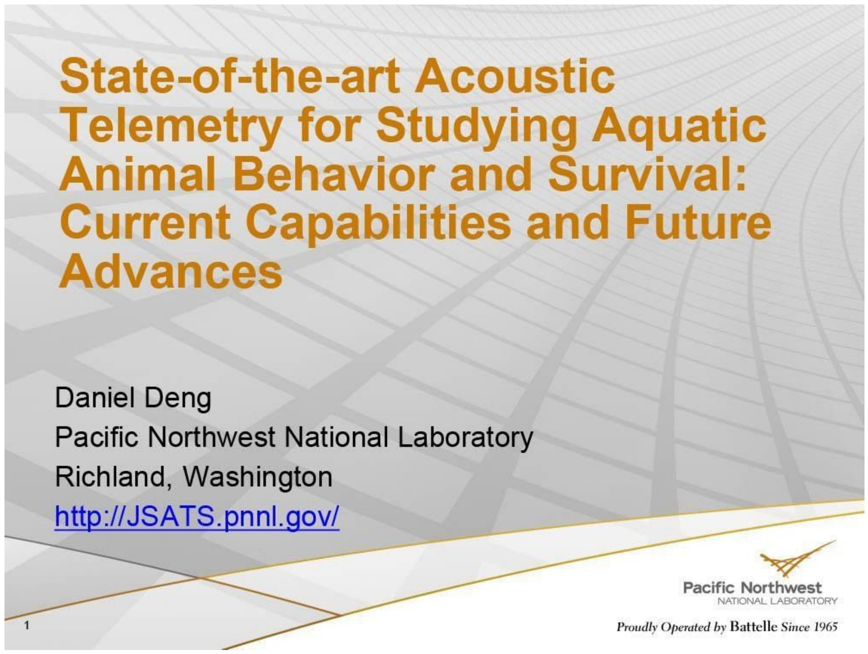
Underwater Optical Communications

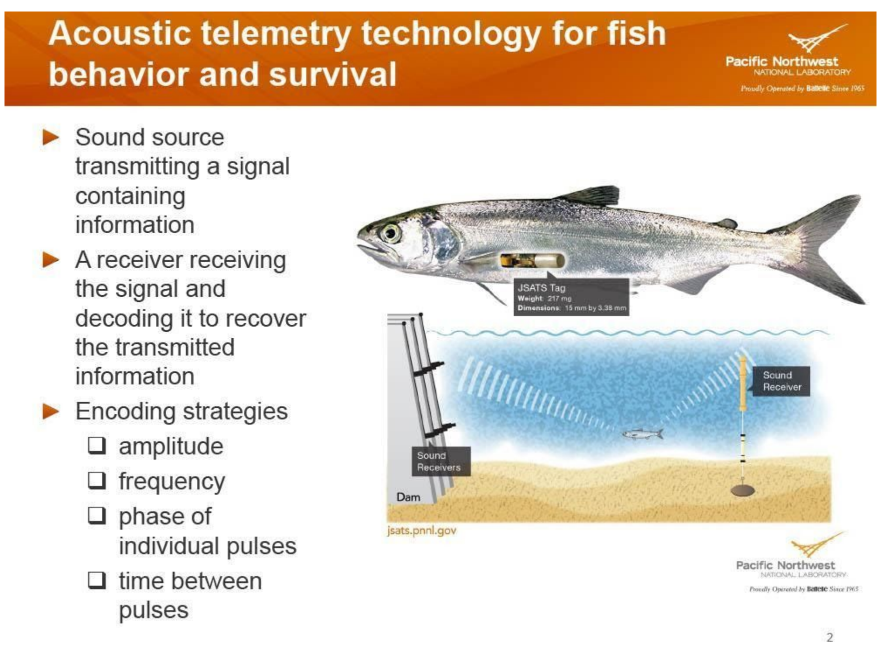



UNCLASSIFIED // DISTRIBUTION A
Communications using RF Field Detectors
EM Field Attenuation
Near ~ $1/R^3$, Radiating ~ $1/R$
Conductive media ~ $e^{-\delta/R}$
High Sensitivity Quantum Receivers
OPM
Optical pumping
Main field direction
Comm signal
Design, Capabilities, & Evaluation
Measurement noise floor
Frequency
Compact
+
High Sensitivity
+
Balanced Detection for Noise Suppression

Session 2 Short Talk

"State-of-the-art Acoustic Telemetry for Studying Aquatic Animal Behavior and Survival: Current Capabilities and Future Advances"
-- Daniel Deng (PNNL)





Animation showing behavior of fish approaching the dam

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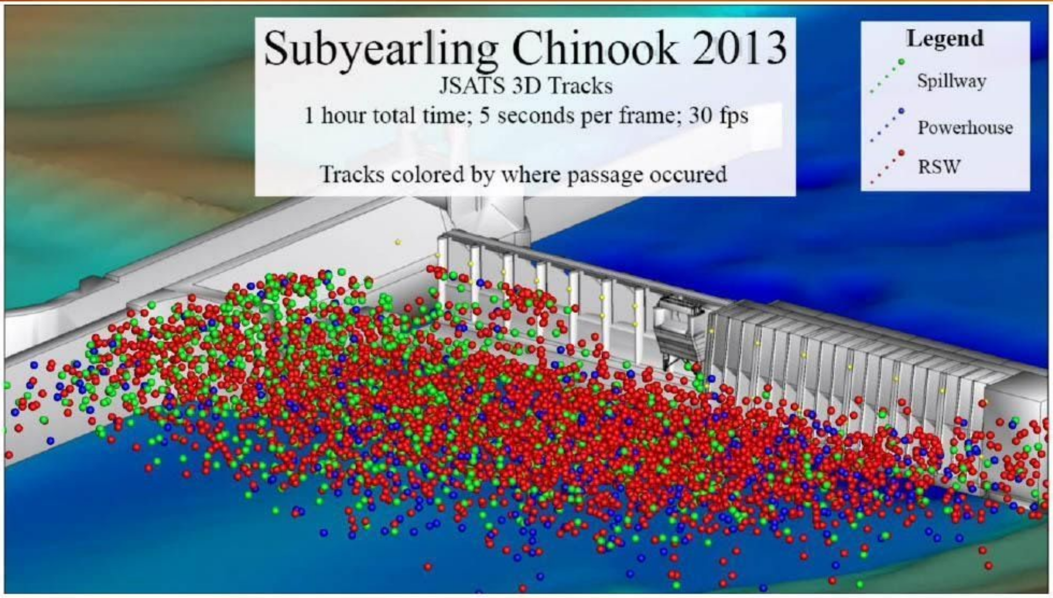

Also available at: https://youtu.be/m_0nyc3bGds

3

New trends for biotelemetry

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- Smaller and lighter transmitter
- More powerful transmitter in detection range
- Long-lasting transmitter including energy-harvesting sensing platform
- Multi-parameter (environmental, physiological, and location) sensing including bio-logging
- Flexible or stretchable: Emerging flexible and stretchable electronics will accelerate the development of novel flexible or stretchable sensors for bio-integrated applications
- Cloud-based and real-time system to estimate behavior or survival of tagged aquatic animals
- Machine learning to improve 3D tracking accuracy and large data processing

4

Suite of Acoustic and Radio-frequency Transmitters

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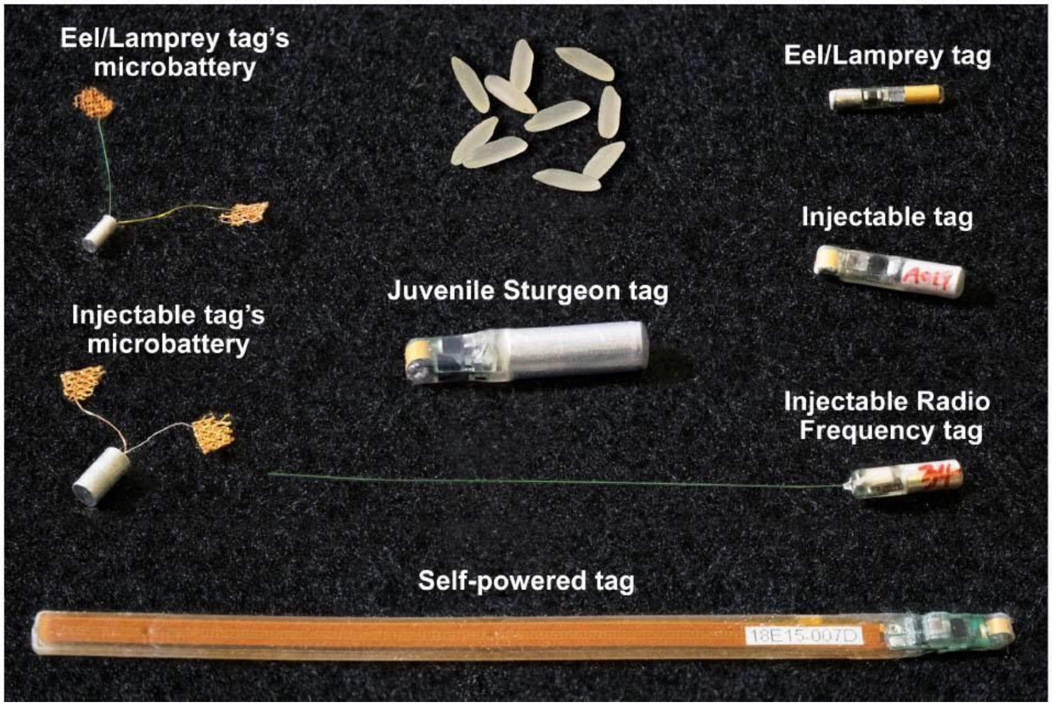

First Generation Juvenile Lamprey/Eel Acoustic Transmitter*

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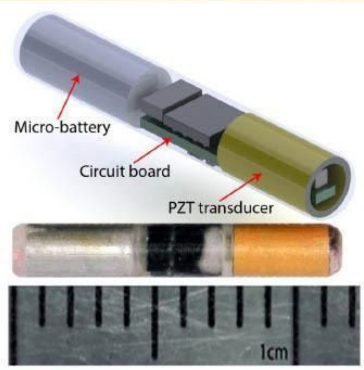
- Dimension: 12.0 mm x 2.0 mm
- Dry weight: 0.08 g
- Wet weight: 0.04 g
- Source Level: 148 dB
- Configurable pulse rate interval & tag code
- Optional temperature, alternating code, and hibernation mode
- Tag life: ~30 days at 5-s pulse rate interval
- Demonstrated feasibility in lab and field conditions

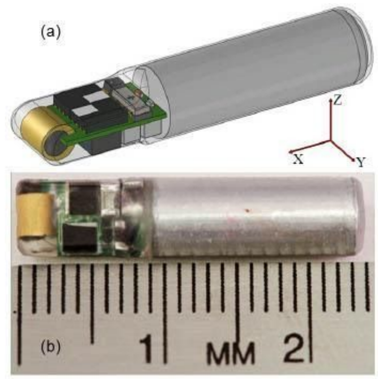


*Available for licensing; patented

6

Long-term juvenile sturgeon tag specifications*

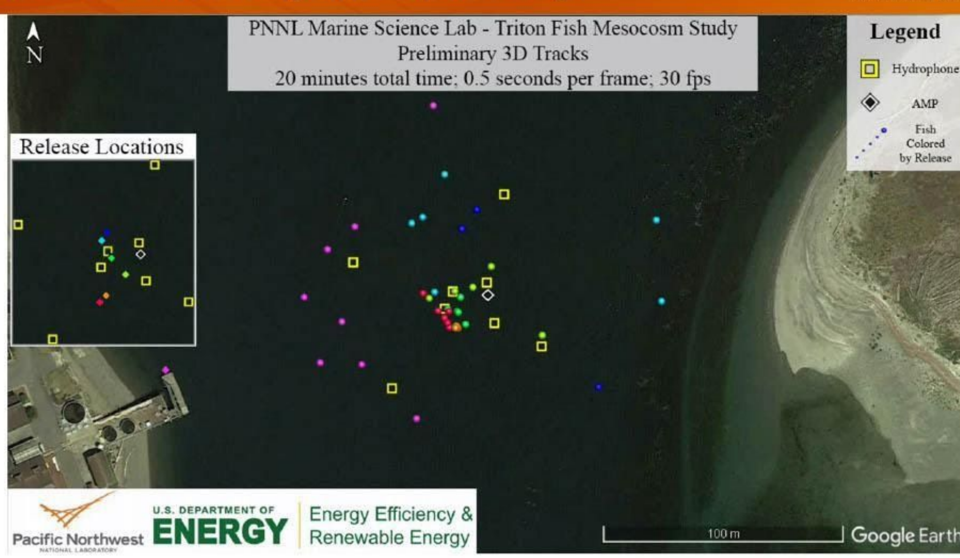
- Dimension: 24.2 mm x 5.0 mm
- Dry Weight: 718 mg
- Wet Weight: 219 mg
- Volume: 419 mL
- Source Level:
  - 161 or 163 dB at zero deg
- Configurable pulse rate interval & tag code
- Optional temperature, alternating, and hibernation mode
- Tag Life: 365 days at 161 dB and 15-s pulse rate interval



*Available for licensing; patented

Lu, J. et al. 2016. A small long-life acoustic transmitter for studying the behavior of aquatic animals. Review of Scientific Instruments, 87(11), 114902.

Application of Sturgeon Tag: Triton Fish Mesocosm Study in Sequim Bay*



Animation also available at: https://youtu.be/gQ4ydPwhY0g

Staines et al. 2019. "Using acoustic telemetry for high resolution sablefish movement informing potential interactions with a8 tidal turbine." In Proceedings of OCEANS 2019 Seattle.

Self-powered acoustic transmitter*: Benchtop testing

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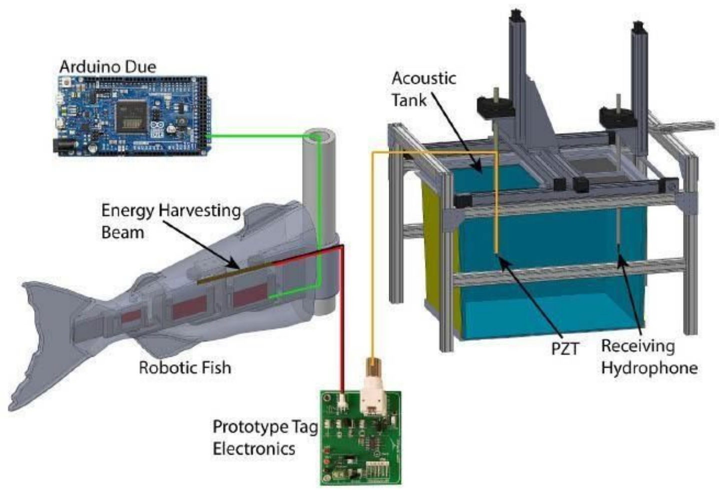

*Patent pending

- Li H, C Tian, and Z Deng. 2014. "Energy Harvesting From Low Frequency Applications Using Piezoelectric Materials." Applied Physics Reviews 1(4):041301.
- Li H, C Tian, J Lu, MJ Myjak, JJ Martinez, RS Brown, and Z Deng. 2016. "An Energy Harvesting Underwater Acoustic Transmitter for Aquatic Animals." Scientific Reports 6:33804. doi:10.1038/srep33804

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Self-powered acoustic transmitter

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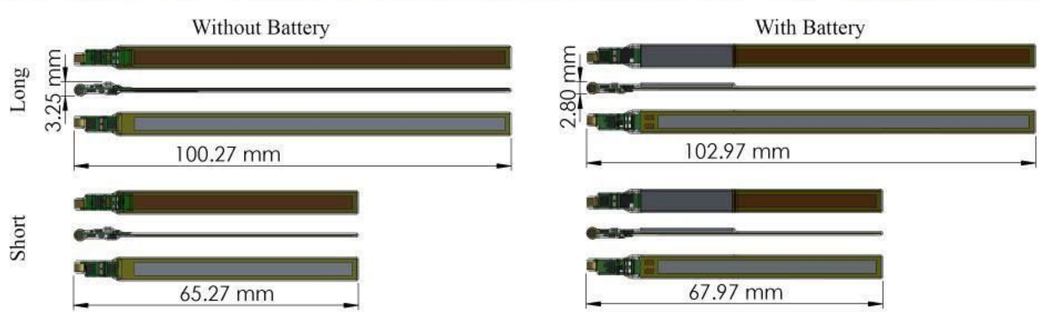
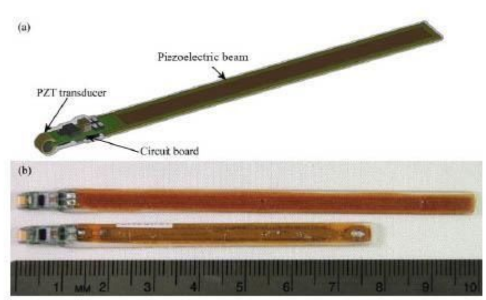


- Option 1 (i.e. "without battery"): The weights are 1.05 and 0.80 grams, respectively.
- Option 2 (i.e. "with battery"): The weights are 1.10 and 0.85 grams, respectively.
- Tag lengths can vary based on power requirements and fish characteristics of specific applications.



* The short tag in the photo used an off-the-shelf piezoelectric beam instead of a custom one and thus was slightly longer than the one shown in the CAD.

Bio-logging: similar trend for marine environment

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Lowerre-Barbieri, Susan K., et al. "**The ocean's movescape: fisheries management in the bio-logging decade (2018–2028).**" ICES Journal of Marine Science 76.2 (2019): 477-488.

Bio-logging and fisheries management 481

Marine fish movement data—challenges and solutions

There are several key challenges to obtaining movescape scale data for marine fish, including the size of the ocean (363 million km^2), the lack of GPS capacity in the marine environment, life history patterns, and high harvest rates. The ocean covers 71% of not yet functional in the marine environment. Small injectable tags (216 mg) are being used to track smolts by the Juvenile Salmon Acoustic Telemetry System (Deng *et al.*, 2017) at population scales (~28 000 fish) and at high spatial resolution (Li *et al.*, 2015). Similar capacity and sample size are expected in marine systems in the near future, given trends in increasing micro-battery capacity (Wang *et al.*, 2015).

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Lab-on-a-Fish Acoustic Transmitter & Data Logger*

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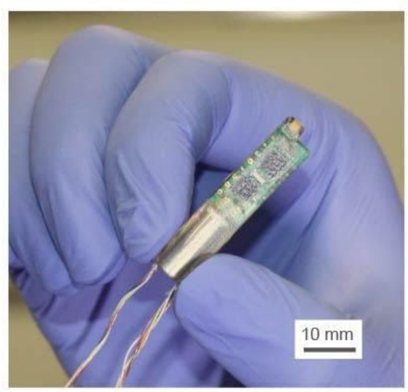
- Dimension: 5.5 mm x 8.0 mm x 37.7 mm
- Dry Mass: 2.4 g
- Wet Mass: 0.8 g
- Volume: 1.6 mL
- Source Level: 158 dB at 0°
- Configurable pulse rate interval & tag code
- Configurable physiological & environmental & physical sensors
- Tag life: > 2 months at 0.5-s pulse rate interval and 15-min measurement interval



*Available for licensing, patent pending

Technical contact: Daniel Deng, (509) 372-6120, zhiqun.deng@pnnl.gov
Commercialization contact: Sara Hunt, (509) 375-6555, sara.hunt@pnnl.gov

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Bio-logging: Lab-on-a-fish

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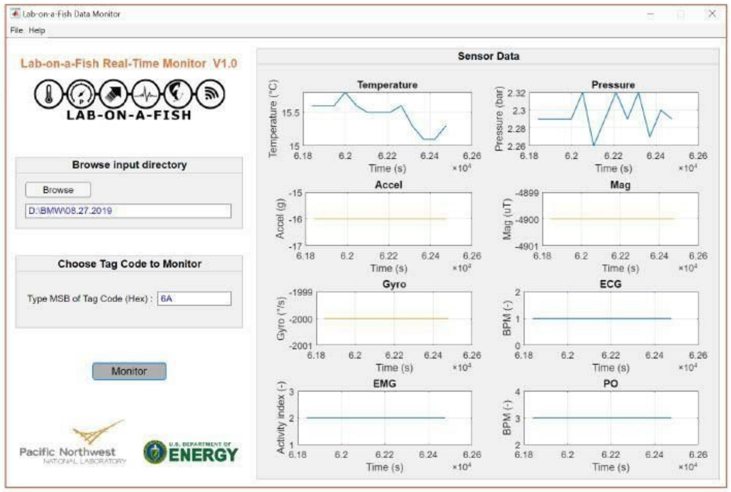
- Physiological
  - Electrocardiogram (ECG)
  - Electromyogram (EMG)
  - Pulse oximetry
- Environmental
  - Magnetic field
  - Temperature
  - Pressure
- Physical
  - Gyration
  - Acceleration



*Available for licensing; patent pending

13

A Cloud-based Autonomous Acoustic Receiver for Monitoring Real-Time Fish Survival

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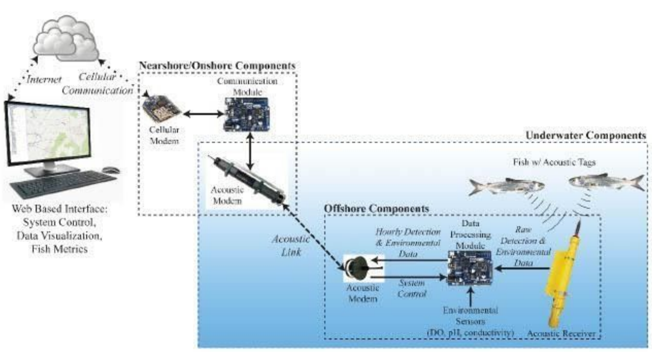
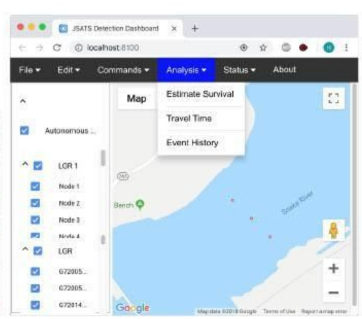
- Remote and real-time data acquisition
- Remote health monitoring of acoustic receivers
- Remote monitoring of environmental conditions
- User-friendly and real-time info on fish survival metrics





Yang et al. 2019. "Design and implementation of a real-time underwater acoustic telemetry system for fish behavior study and environmental sensing." In Proceedings of OCEANS 2019 Seattle.

14

Next frontiers

- Smaller, lighter, more powerful transmitter
- Long-lasting transmitter: self-powered platform
- Bio-logging sensors
- Flexible or stretchable sensors
- Cloud-based and real-time system to estimate behavior or survival of tagged aquatic animals using edge-computing
- Machine learning / deep learning for aquatic animal detection
- Sensing and data telemetry in extreme environments
- Only way to achieve these goals is multi-disciplinary approach and close collaboration between stakeholders nationally and internationally

15

Acknowledgements

- U.S. Department of Energy Water Power Technologies Office
- U.S. Army Corps of Engineers
- Electric Power Research Institute
- Grant County Public Utilities District
- Idaho Power Company
- US Bureau of Reclamation
- US Fish and Wildlife Service
- PNNL LDRD Program
- Numerous DOE/USACE/ PNNL staff

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Thank you

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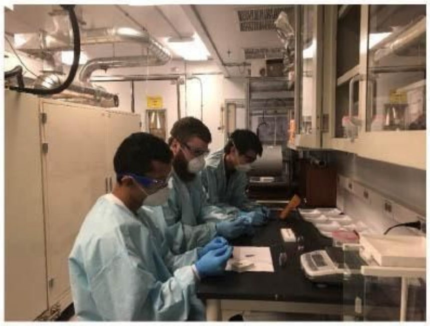

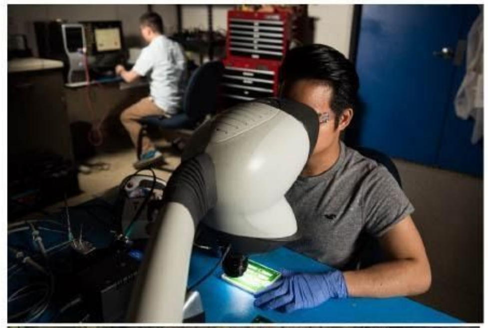

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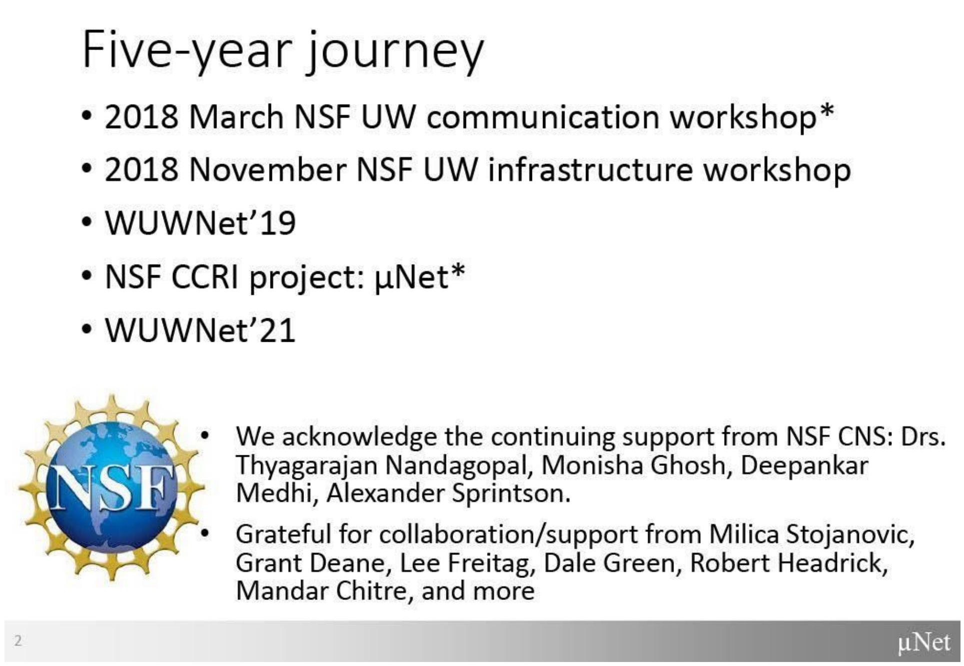
Zhiqun.deng@pnnl.gov; http://JSATS.pnnl.gov/

Session 3 Short Talk

"Infrastructure to Advance Mobile Underwater Wireless Networking Research"

-- Aijun Song (University of Alabama)



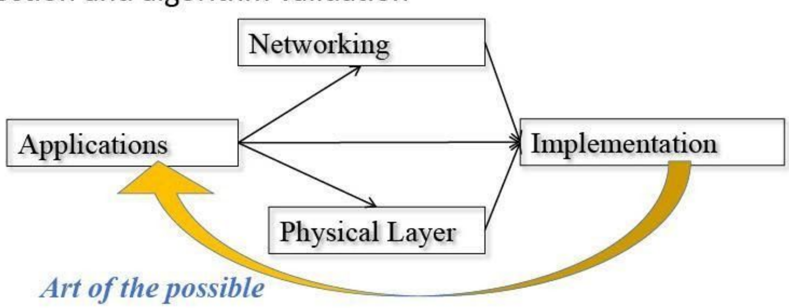
Two workshops in 2018

- Supported by from NSF CNS
- ~60 participants in March
- ~30 participants in Nov

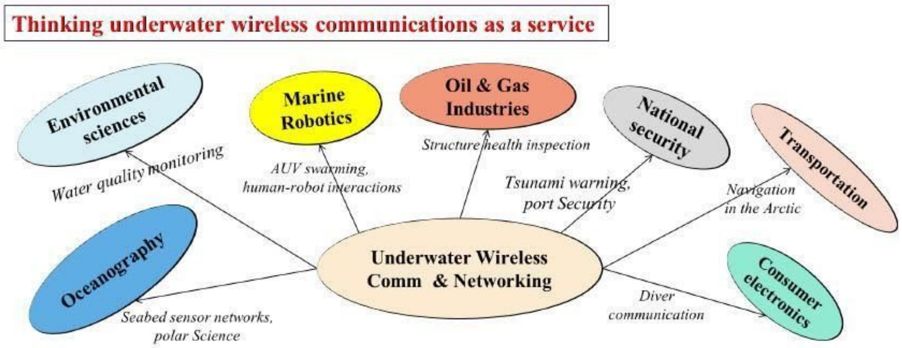
Application-Driven Road Map

- Strong need to broaden research participation
  - Multi-disciplinary collaboration with industrial partnership
  - Open-source software/simulators and affordable & miniaturized hardware
  - Common test grounds
  - Community infrastructure to lower thresholds for data collection and algorithm validation

Application-specific solutions: No one-size-fits-all



Underwater robotics as the future direction



- Research directions:
  - Reliable communications and networking among fleets of AUVs
  - Integration of sensing, communication, and navigation solutions
  - AUV swarming and autonomy research with realistic underwater communication constraints

Common test ground; Open architecture; Simulation-Experimental Gap

- Urgent need to establish a public repository of channel responses & measurements for research, algorithm validation and performance prediction
  - Typical channel types (3-10 of them)
  - Statistical model based on channel responses
- Software-defined, information (or content) centric, mobility-aware architectures at the network layer
  - Address large delay and low bandwidth, support robustness/reliability
  - Application-optimized hierarchical, hybrid architecture
- Gap between Networking Simulations and Experimental results

A. Song, M. Stojanovic, and M. Chitre, "Editorial Underwater Acoustic Communications: Where We Stand and What Is Next?" IEEE JOE, Jan. 2019.

Infrastructure needs

- Shared infrastructure: Change the current mode that everyone needs to build or purchase their own robots or modems
  - Shared infrastructure should be installed and maintained by certain institutions
  - Shared access to an instrument pool
- Roles of the community infrastructure: Supporting research activities and proposals of the community members, future workforce development, outreach, and public engagements
- Acoustic ranges: At least one open-access acoustic range for acoustic transmissions
  - Start with fixed node structure and standard transmission format, standard channel probes followed by a data payload
  - Design for directive transmissions and adaptive transmissions
  - Upgrade later to mobile nodes
- **Visit: http://uwa.ua.edu/ for presentations and executive summaries**

7 µNet

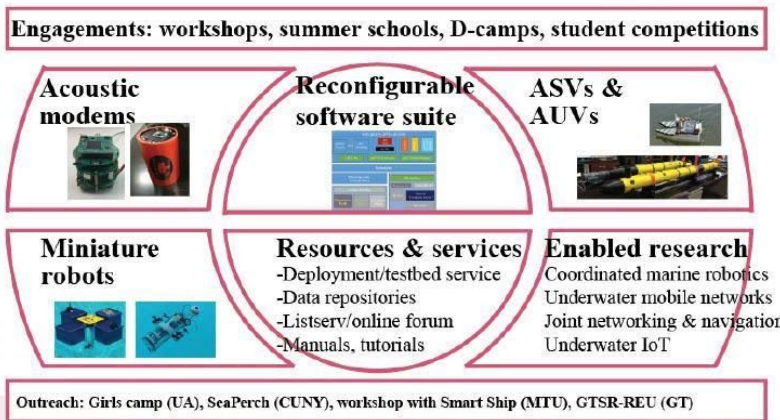
NSF CCRI: µNet

- Objective: developing a community-shared, open-source, open-architecture infrastructure, µNet, for mobile underwater wireless networks.
- Service-orient architecture: Different from the current network- or robot-centric architectures.
- Multidisciplinary team: UA (Song [ocean acoustics/signal processing] and Hong (networking); GT (Zhang [control/robotics]), CUNY (Peng [MAC/integration]; MTU (Wang [Communications])

8 µNet

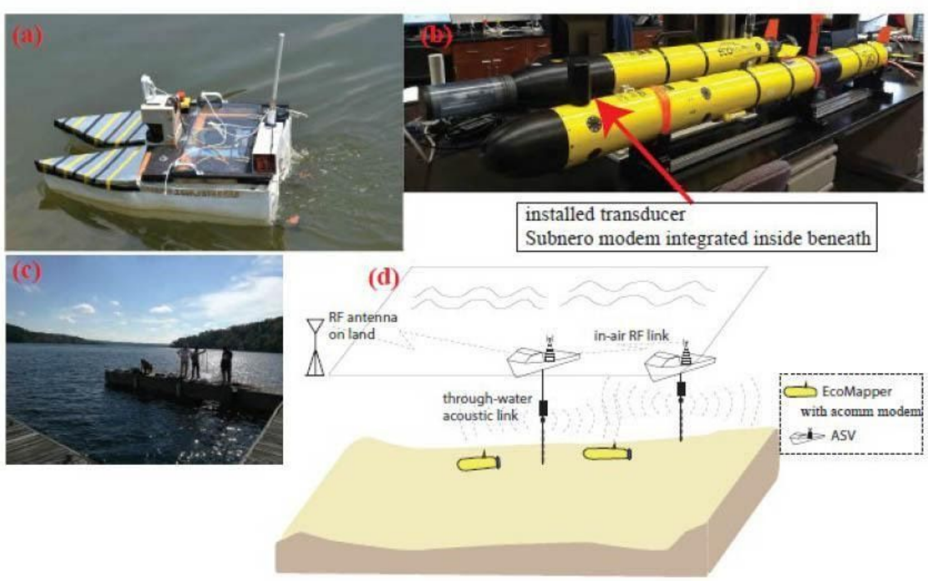
Community-shared, open-source infrastructure

- Open-source, re-configurable software suites, µNet
- Low-cost or software-defined acoustic modems
- Miniaturized aquatic robots for lab tests==➔ indoor testbed
- Field-deployable autonomous surface vehicles (ASVs) and autonomous underwater vehicles (AUVs) for field deployments==➔ lake testbed



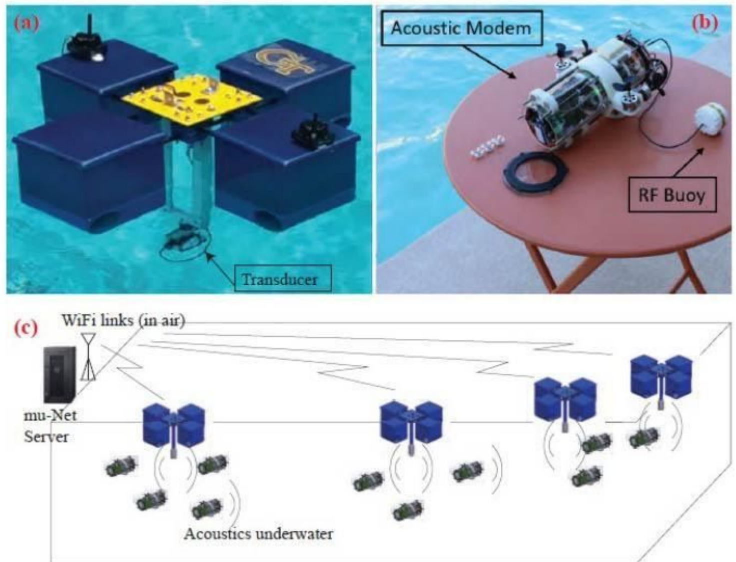
Lake testbed

- AUVs/ASVs + acoustic modems + µNet software



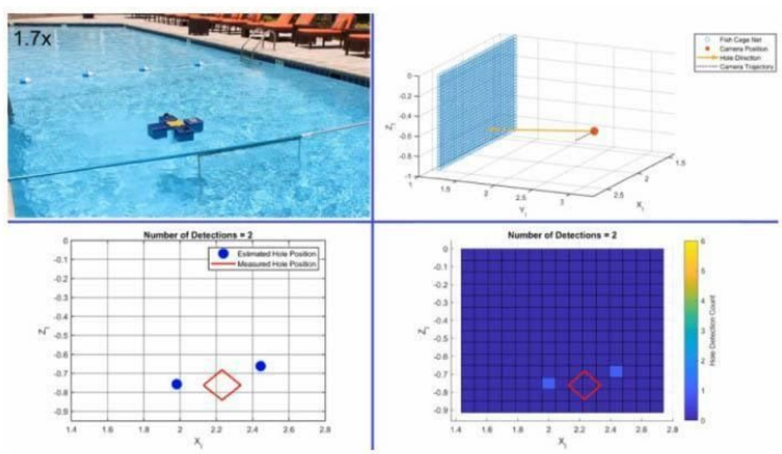
Indoor testbed

- GT-MUR, GT-OSV + acoustic modems + µNet software



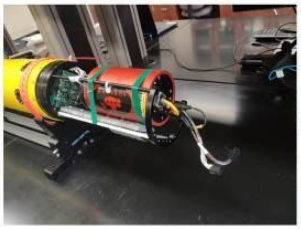
Indoor testbed (2)

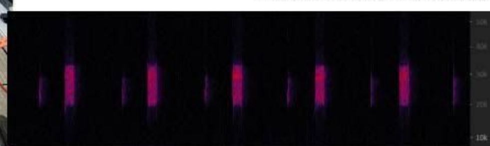
- GT-OSV and GT-MUR: both tested and integrated with acoustic modems



Lake testbed status: EcoMapper+AcommModem

Area: 1 km x 2 km
Depth: ~ 20 m





WUWNet'19 and WUWNet'21

- WUWNet'19: Promote close interactions between underwater comm/networking with marine robotics: Keynotes and special sessions
- WUWNet'21 (virtual): Infrastructure focused discussions

- 2018 NSF UWA Workshop website: http://uwa.ua.edu/
- Contact: song@eng.ua.edu
- Website: https://ajsong.people.ua.edu/

Session 3 Short Talk

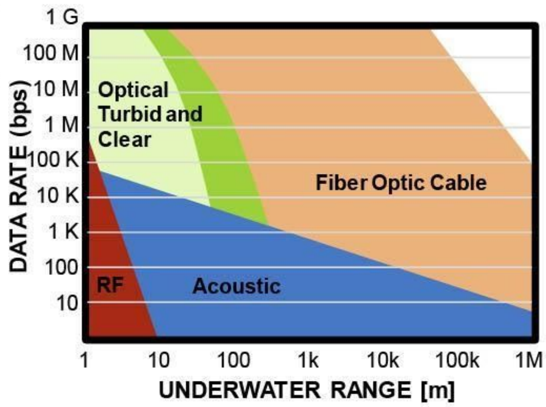
"Networking and Acoustic Communications at NRL"

-- Lloyd Emokpae (NRL)

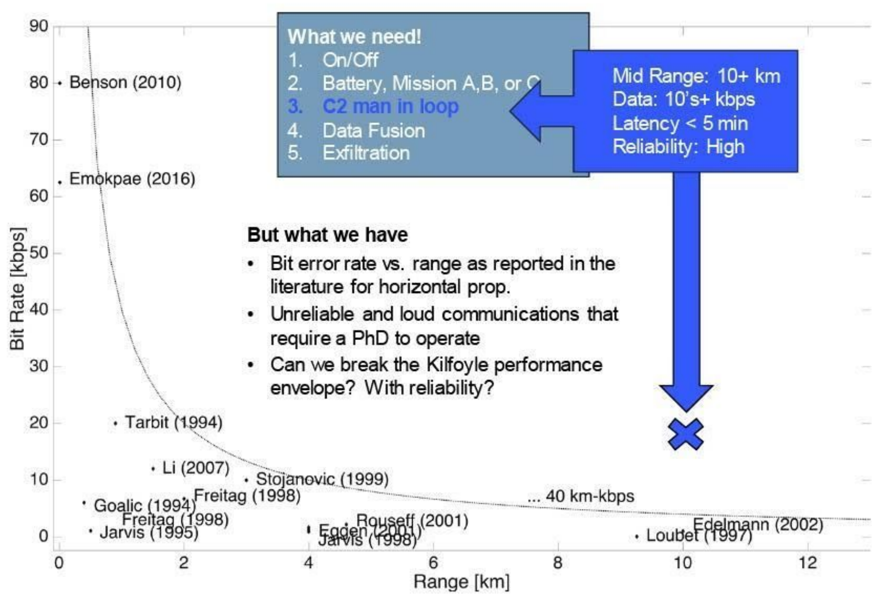
Underwater Communication

Underwater communications can take many forms e.g. acoustic, fiber optic, RF, and optical.

- Due to attenuation, acoustics is the *de facto* method of unwired long range acoustic communications.
  - Radio Frequencies 50 dB/m @ 1 MHz
  - Acoustics 0.3 dB/m at 1 MHz
- Key Challenges:
  - Multipath (echoes from boundaries)
  - Low SNR (high noise and attenuation)
  - Slow speed of sound
  - Temporal/spatial variability
  - Lack of space/time information



State of the Art Range and Rate



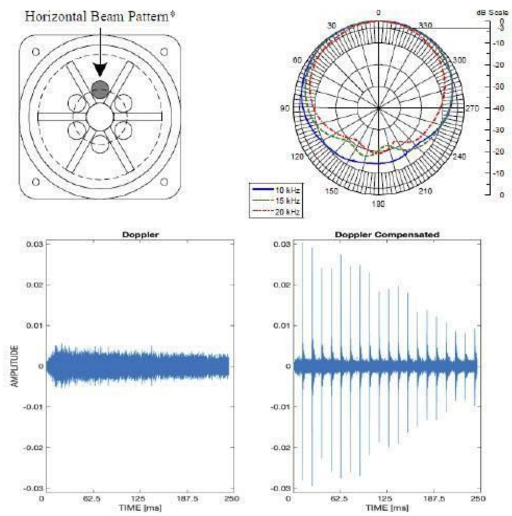
Network | Data-Link | Physical

Reliable Underwater Communication

Modem/Physical Layer

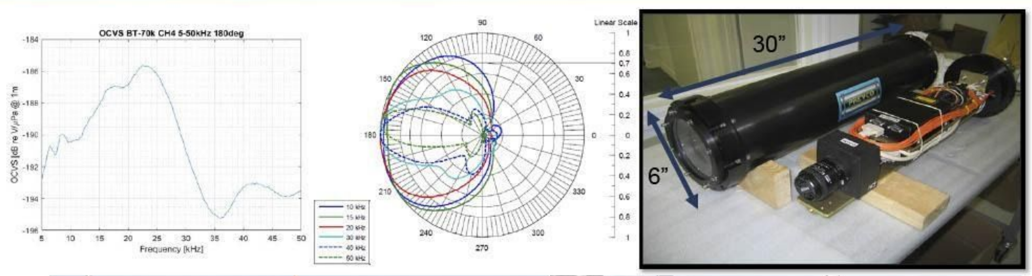
Reliable Communications

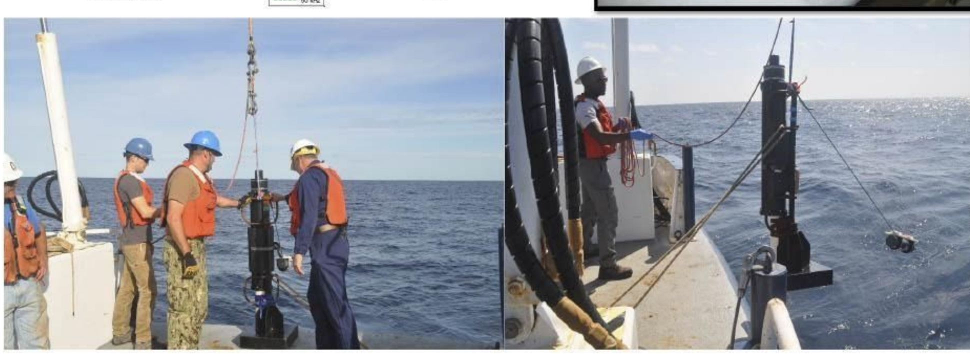
- Create reliable communication system that enables data fusion and man-in-the-loop control
- Features:
  - 1 to 10 km range
  - 100 to 1000 bps data rate
  - < 10 min latency
  - Highly reliable physical layer
    - Multi-modal directional transducer
    - Data modulation
  - Directional networking
    - Directional MAC
    - Neighbor discovery
  - Using Spread Spectrum Communication



Network | Data-Link | Physical

NRL Reconfigurable Modem (RAMP)





Network | Data-Link | **Physical**

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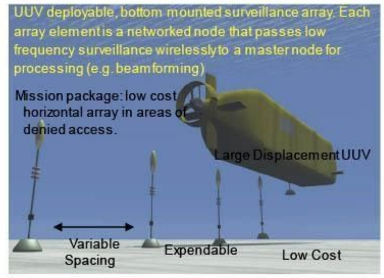
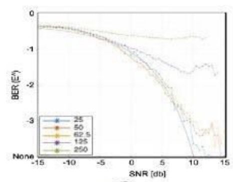
Underwater Acoustic "Bluetooth"

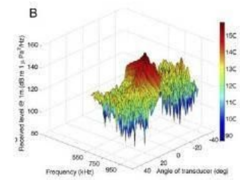
Modem/Physical Layer | Low Probability of Detection

Autonomous Networked Array Using Low-Complexity Communications

- Replace vulnerable cables and connectors on bottom mounted arrays with an ultrasonic wireless network capable of coherent array processing.
- Features:
  - Low frequency surveillance with high data rate exchanges via ultrasonic frequencies
  - Self-healing network with low overhead is naturally trawl resistant
  - No multipath via transducer directivity i.e. low complexity modem even in shallow sand
  - BPSK 50, 62.5, & 125 kbps (demultiplied signal sampled at 250 kS/s) @ 5 m
  - Atomic clock to coherently process low frequency acoustic signals ± 5 x 10-11 accuracy w/ 115 mW power consumption







Network | Data-Link | Physical

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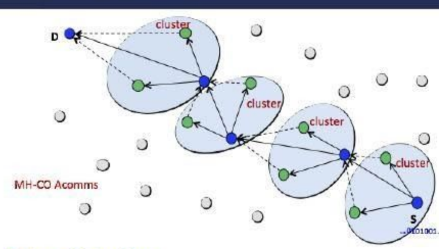
Multihop Cooperative Network

Networking

Multihop Cooperative Underwater Acoustic Communications for Time-Critical Missions

- Develop multi-hop cooperative (MH-CO) ACOMMS with reliable data transfer and short latency in a underwater acoustic network (UAN)
- Features:
  - Novel clustering scheme to reduce latency by utilizing other nodes to forward on communications
  - Reliable method to route cluster hopping robust to impulsive noise (e.g. snapping shrimp)
  - Pick path with minimum possible end-to-end propagation delay
  - Showed BER improvement with additional cooperative nodes in both string and grid topologies in at-sea experiments
  - Equal energy usage across network



Robust Routing

PN Code Length	127	255	511
Success Rate	43%	100%	100%

Improved Throughput

String Topology	CN = 0	CN = 1	CN = 2
Uncoded BER	13.7%	3.5%	1.3%
Packet Loss Rate	83%	13%	1.8%
Grid Topology	**CN = 0**	**CN = 1**	**CN = 2**
Uncoded BER	15.4%	3.7%	4.7%
Packet Loss Rate	86%	14%	2.1%

Session 4 Short Talk

"Applications of Acoustic Communications"

-- Lee Freitag (WHOI)

Applications of Acoustic Communications

Lee Freitag

Woods Hole Oceanographic Institution

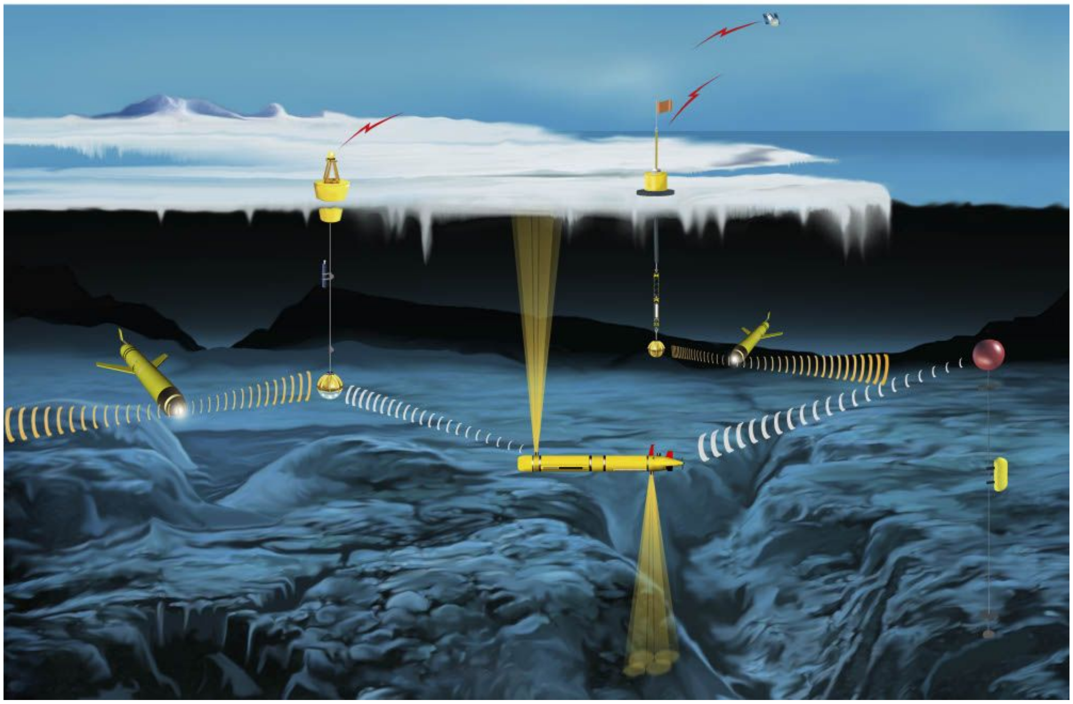
NSF BLUE UCI Workshop 2021

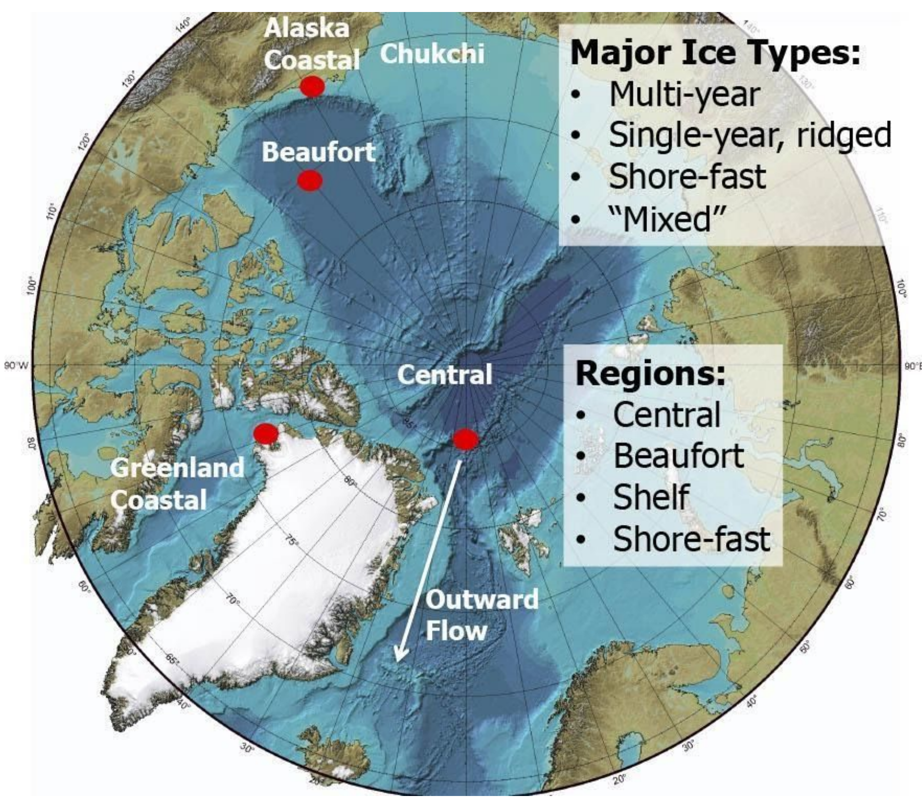
Themes for the Talk

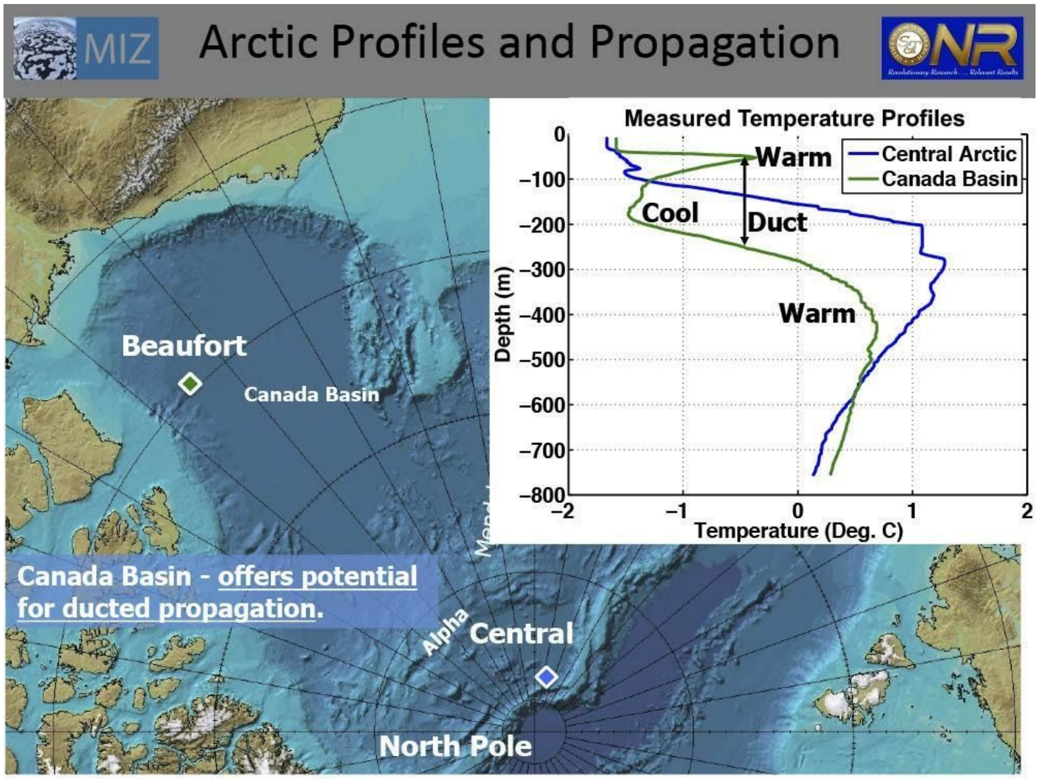
- Applications & Missions
- Range scales
- Locations – Geographical
  - Arctic
  - Equatorial

2

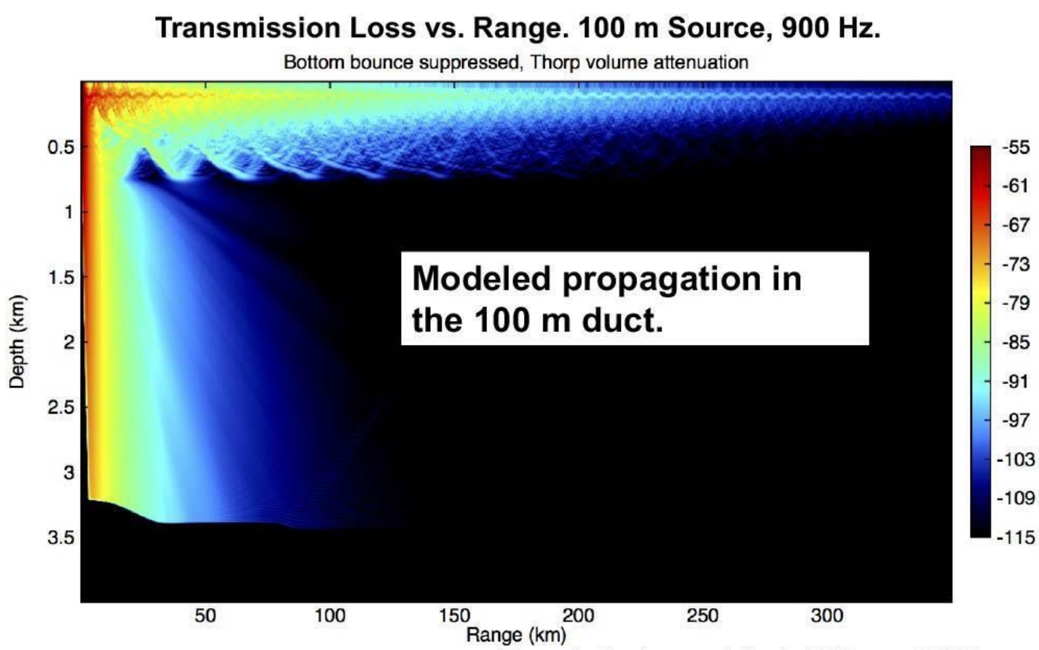
Arctic: Under-ice autonomous systems allow mapping the underside of the ice and upper layers, hidden to satellites.





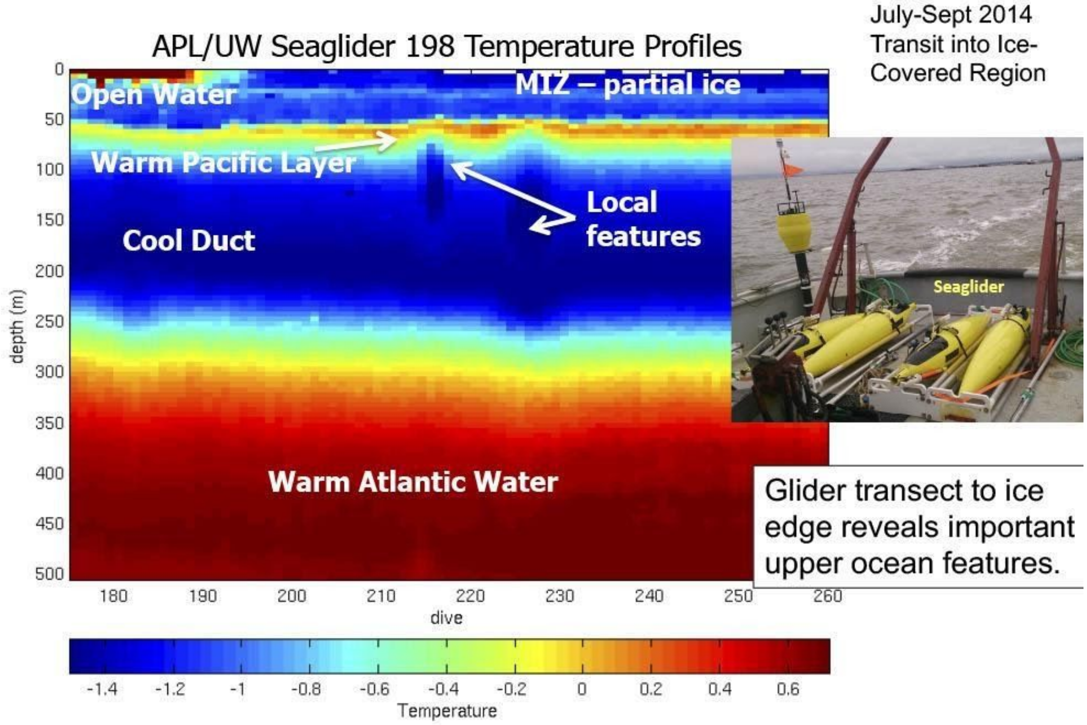


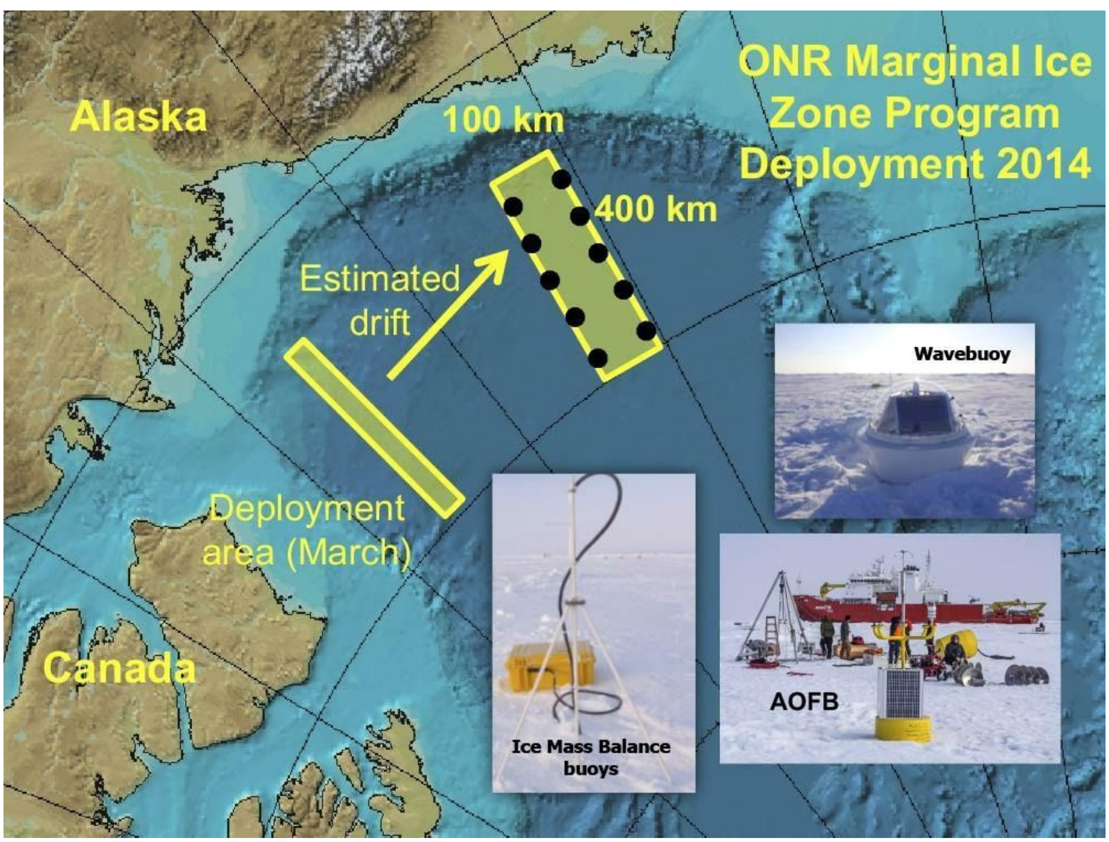
Modeled Propagation



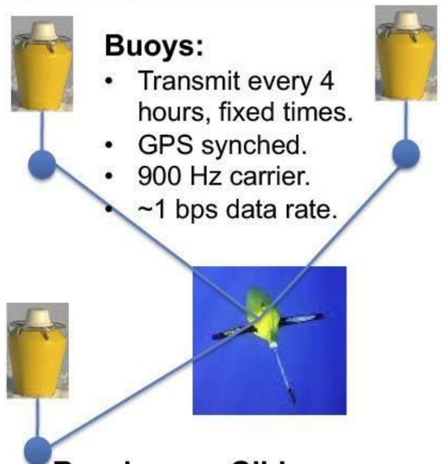
Transmission loss modeling by K. Heaney, OASIS

Mapping Arctic Ocean Temperature





Acoustic Navigation System



Buoys:

- Transmit every 4 hours, fixed times.
- GPS synched.
- 900 Hz carrier.
- ~1 bps data rate.

Receiver on Glider:

- Measures time, computes range.
- Decodes location of buoy.
- Ranges and source locations used to compute real-time position.

How Does it Work?

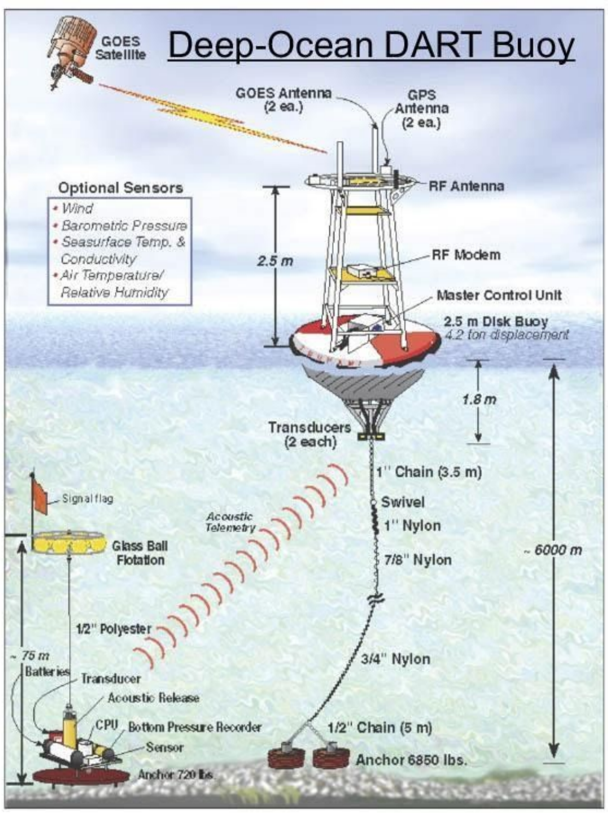
- Ice-based sensor array is mobile.
- Therefore must transmit source positions to allow real-time geo-location by gliders.
- Data transmission capability also means commands can be sent to glider.

Glider Receiver Hydrophone

Glider Receiver Board

Underwater Communications and Ocean Bottom Pressure Sensor Cabled System

Funded by the NSF HAZARD SEES project "Hazards SEES Type 2: From Sensors to Tweeters: A Sustainable Sociotechnical Approach for Detecting, Mitigating, and Building Resilience to Hazards" (Grant 1331463).



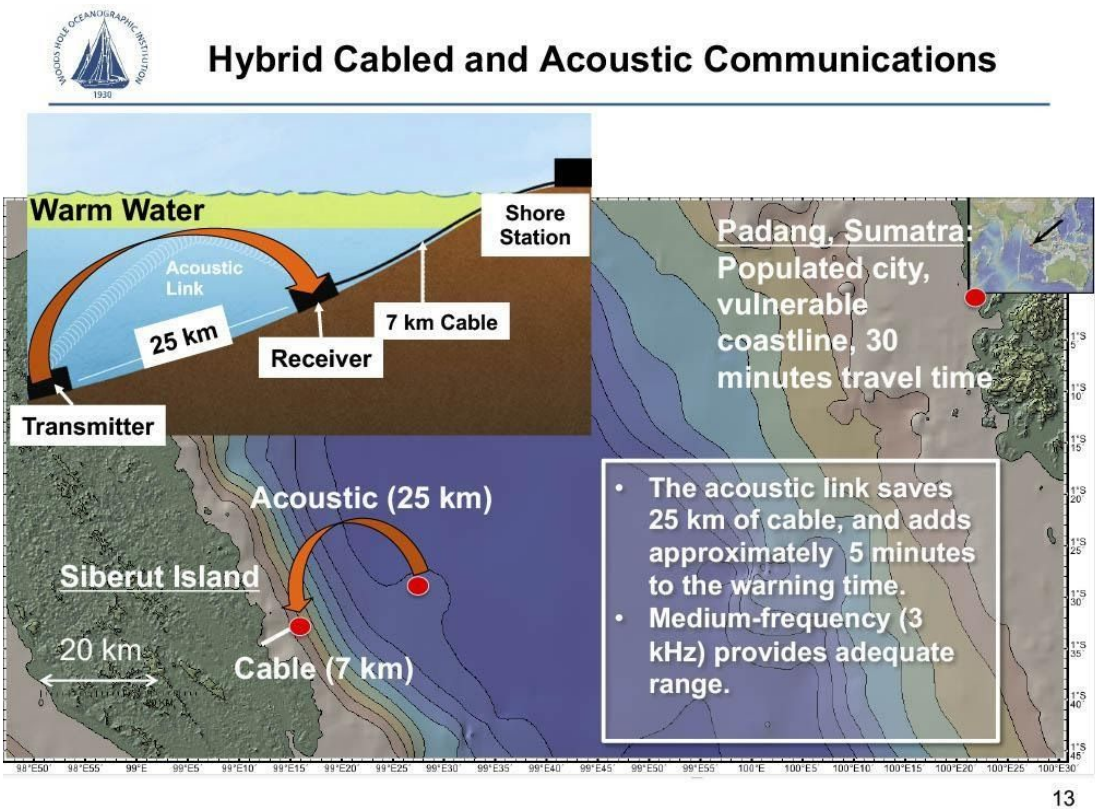
Tsunami Buoys in Indonesia

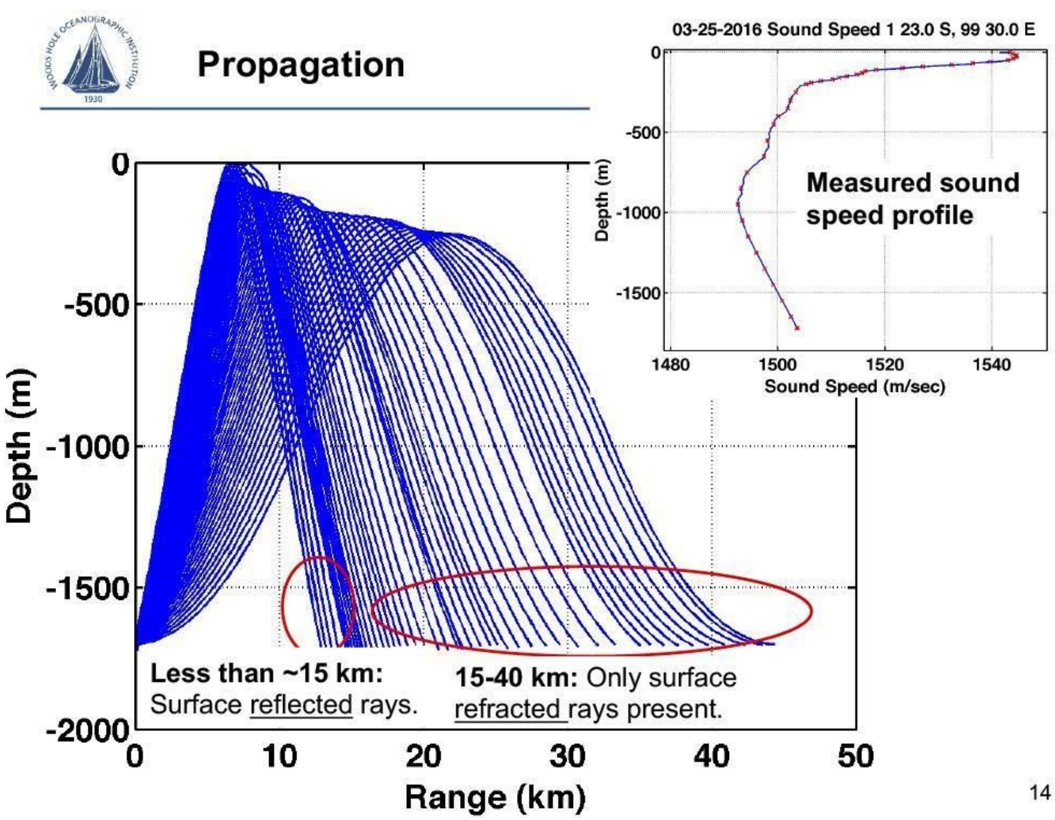
<u>Issue</u>: Many have been vandalized. Near-field buoys are close to shore and likely targets.

<u>Solution</u>: Use cabled pressure sensors. However cost is high.

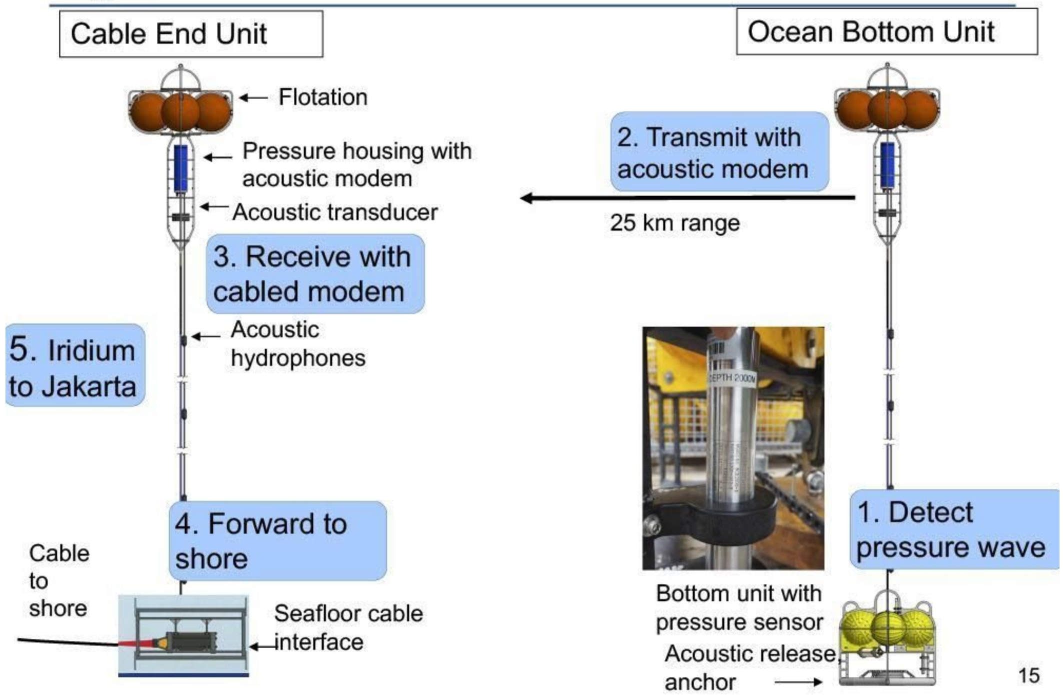
<u>Alternate</u>: Couple MF acoustics (20-30 km) with short cables (5-10 km).

Children using a stolen buoy as a swim platform in a remote village.


Hybrid Cabled and Acoustic Communications
Warm Water
Shore Station
Acoustic Link
25 km
Receiver
7 km Cable
Transmitter
Padang, Sumatra: Populated city, vulnerable coastline, 30 minutes travel time
Acoustic (25 km)
Siberut Island
20 km
Cable (7 km)
• The acoustic link saves 25 km of cable, and adds approximately 5 minutes to the warning time.
• Medium-frequency (3 kHz) provides adequate range.
13


Propagation
03-25-2016 Sound Speed 1 23.0 S, 99 30.0 E
Measured sound speed profile
Depth (m)
Sound Speed (m/sec)
Less than ~15 km: Surface reflected rays.
15-40 km: Only surface refracted rays present.
Range (km)
14

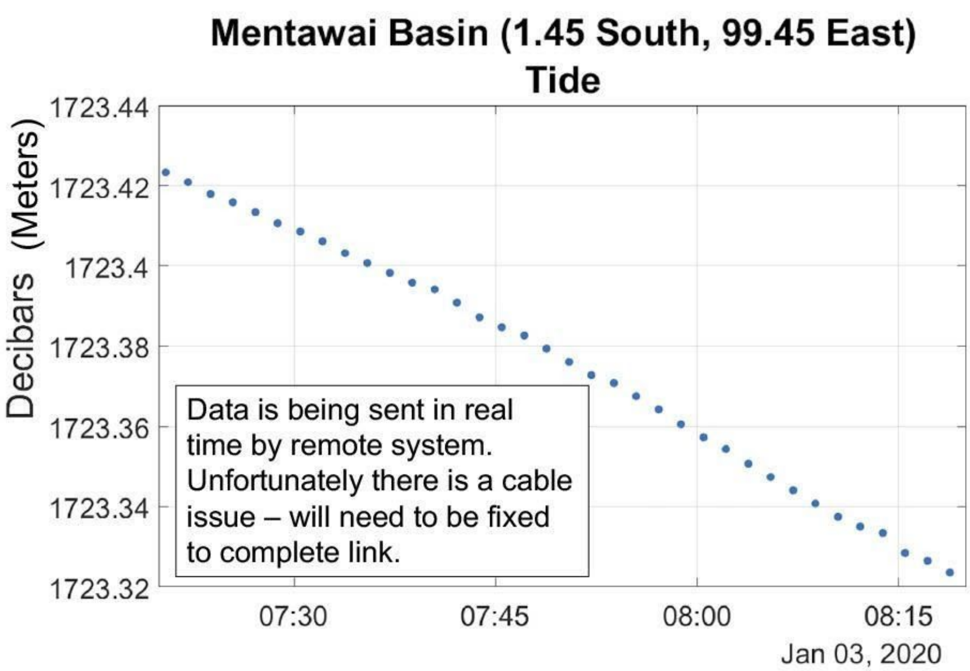
Indonesia Communications System



Deploying Lander with Pressure Sensor

Terminating the Cable on the Ship

Results: Indonesia Remote Pressure Sensor



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Wrapping up:
Suggestions and Take-aways

What do I think about Marine Robotics and Machine Learning?

- Intelligent robotic systems will aid communications networks.
- Environmental adaptability – multiple scales required.
- Cross-over from terrestrial applications will help, need to engage with existing research base.

(Mandar summarized work in this area nicely – no need to repeat!).

Session 4 Short Talk

“Enabling Undersea Persistent Autonomy”

-- Nina Mahmoudian (Purdue)

Enabling Undersea Persistent Autonomy

Nina Mahmoudian, Associate Professor
Purdue University
ninam@purdue.edu
https://engineering.purdue.edu/mahmoudian/

1

Large-scale long-term undersea deployment of autonomous vehicles requires coordination and infrastructure co-design

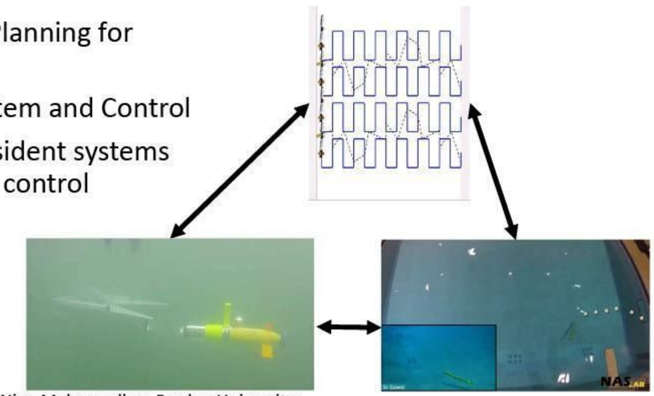
Developing theoretical, computational, and experimental tools to address operational challenges:

- ❑ Smart autonomous energy maintenance
- ❑ Lower deployment and operating costs
- ❑ Increase efficiency, endurance, and persistence

Nina Mahmoudian, Purdue University
2

The goal is to lower deployment and operating costs, while also increasing efficiency, endurance, and persistence through interconnected approach:

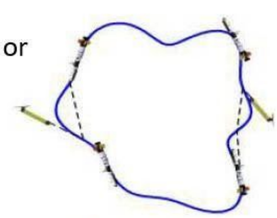
- Collaborative Mission Planning for Resource Allocation
- Integrated Docking System and Control
- Low-cost high-value resident systems with efficient real-time control

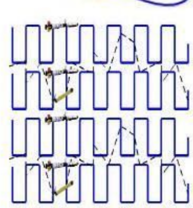


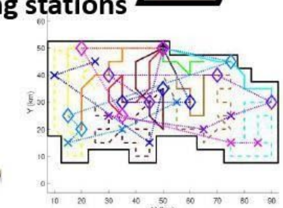
Nina Mahmoudian, Purdue University
3

Developed mission planning architecture for long-term AUV missions with energy replenishment using static charging stations and mobile chargers that is capable of:

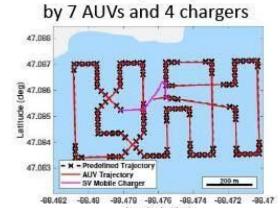
- Finding placement of static chargers or rendezvous locations with mobile chargers
- Planning efficient trajectories for workers and chargers
- Handling multiple workers, multiple chargers with varied characteristics
- Handling worker failures/disturbances managed with online re-planning







Example trajectory followed by 7 AUVs and 4 chargers

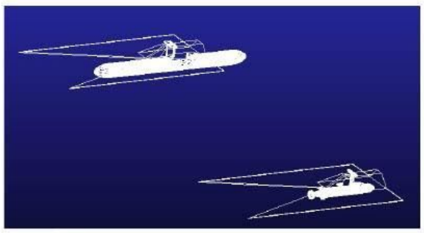


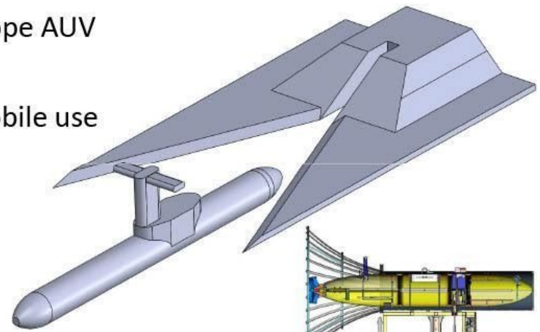
Experimental feasibility validation with Iver3

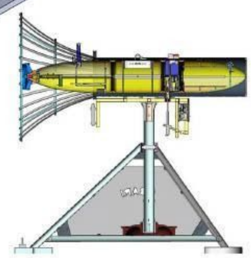
Nina Mahmoudian, Purdue University
4

Existing undersea docking stations are costly, bulky, and vehicle specific. What if we could create a dock that was vehicle agnostic and collapsible?

- Dock must not completely envelope AUV
- Dock must be quick to deploy
- Dock must be streamlined for mobile use

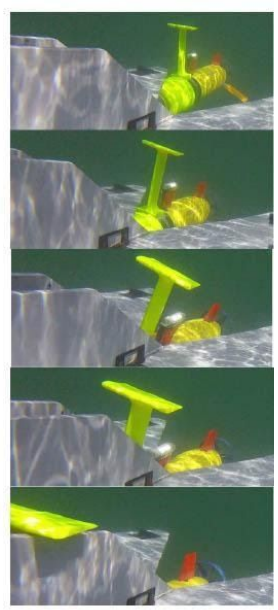






Developed a collapsible portable and vehicle agnostic underwater docking system with:

- Proven adaptability to a wide range of AUV sizes
- Potential to integrate into existing AUV mast
- Control strategy for docking maneuver
- Full simulation in challenging conditions
- Experimental validation with two AUVs



Created mobile docking system taking advantage of the portable collapsible nature of the design

- Mounted the docking station at rear of our costume-made inflatable small USV
- Planar dock design minimally impacts USV performance
- Rear mounted location enables launch and recovery while underway
- USBL communication integrated for docking
- Performing extensive open-water experiments

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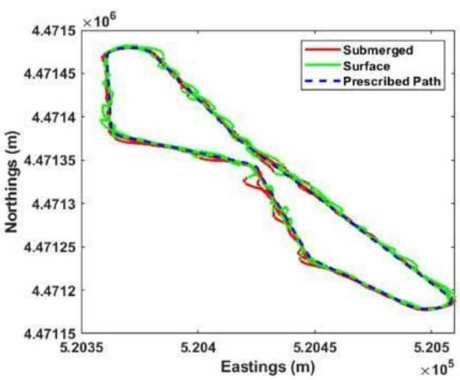
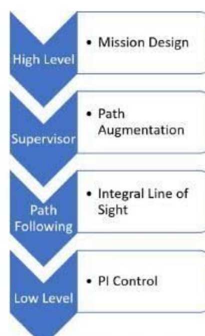
7

To ensure successful approach and rendezvous process, a multi-layer path planner/follower has been implemented with success for both underwater and surface vehicles following complex paths





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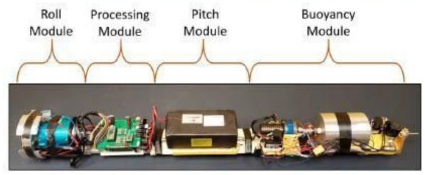
Developed a low-cost agile underwater glider to take advantage of long-term operation of underwater gliders, but increase maneuverability and modularity

- ROUGHIE is the most maneuverable internally actuated underwater glider with 3 meter turn radius
- Perform complex maneuvers 3D space utilizing advanced switching controller to concatenate steady flights
- Capable of operation in shallow water and crowded areas
- Low magnetic and noise signature



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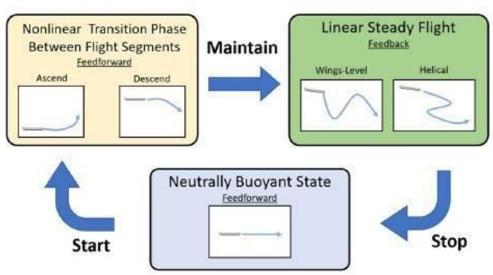
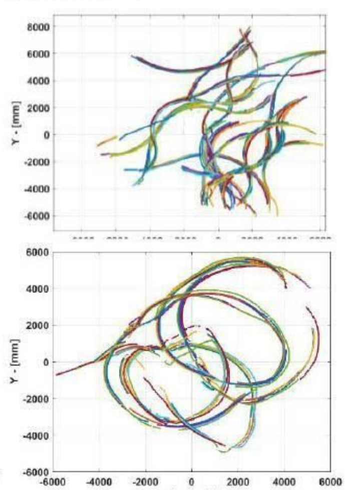
9

ROUGHIE maneuvers are achieved by concatenating wings-level and helical flight and injecting neutrally buoyant transitions





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Key Take-aways

- The integrated planner, docking station, energy carrying agents, and AUV system provide much needed infrastructure for supporting persistent AUV missions away from infrastructure at a very low deployment cost.
- Augmenting proven control methods with machine learning algorithms will result robust autonomous performance of marine robots in face of dynamic unknown conditions.
- The ultimate goal is to create a complete architecture for deployment of a autonomous networked persistent maritime system that can stay in station for long-term.

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Enabling Undersea Persistent Autonomy

Nina Mahmoudian, Associate Professor

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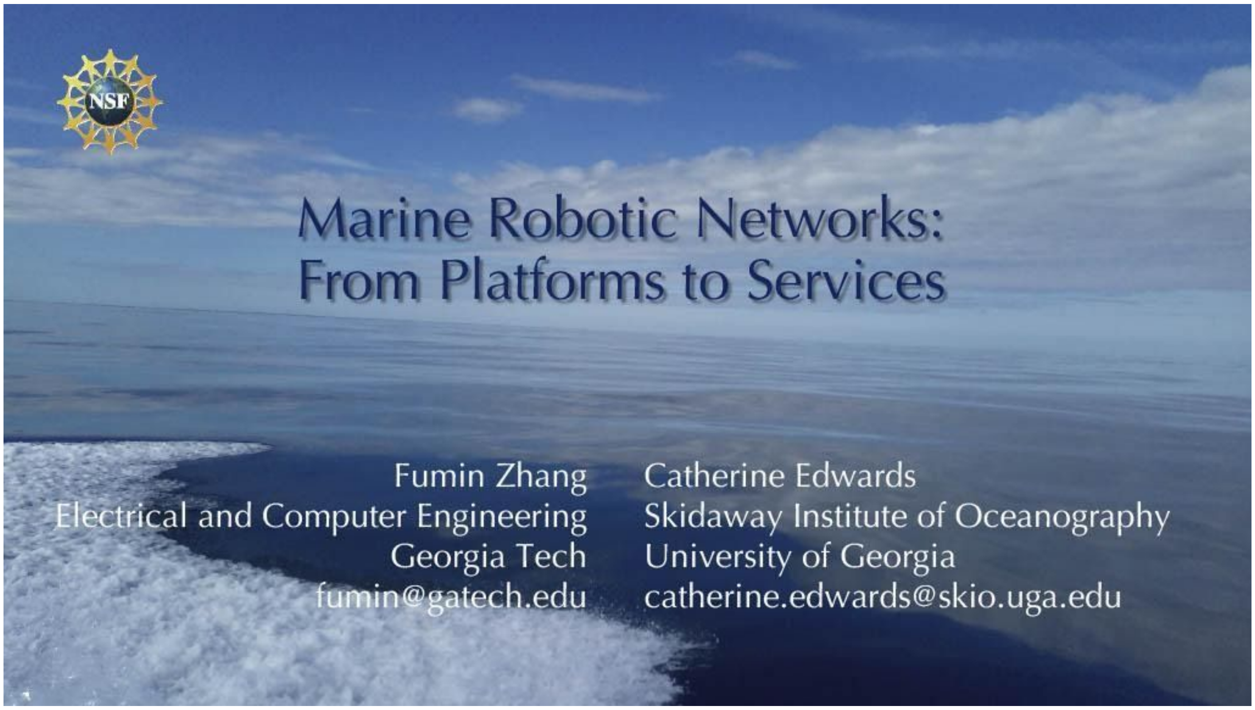
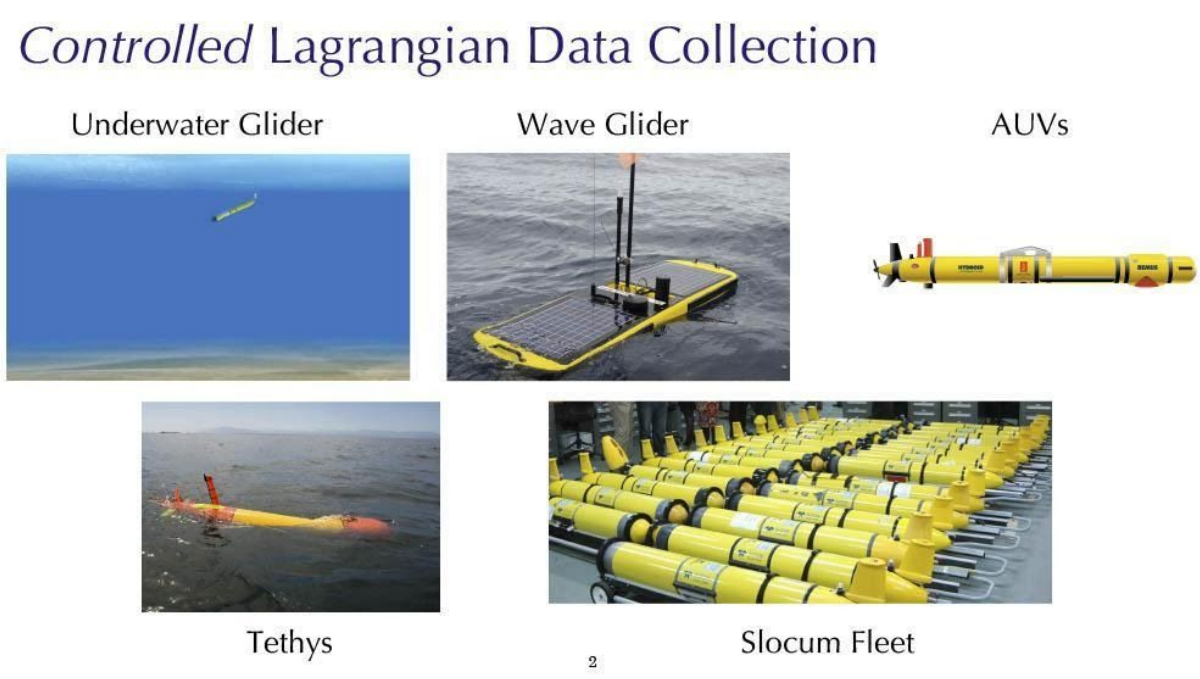
Session 4 Short Talk

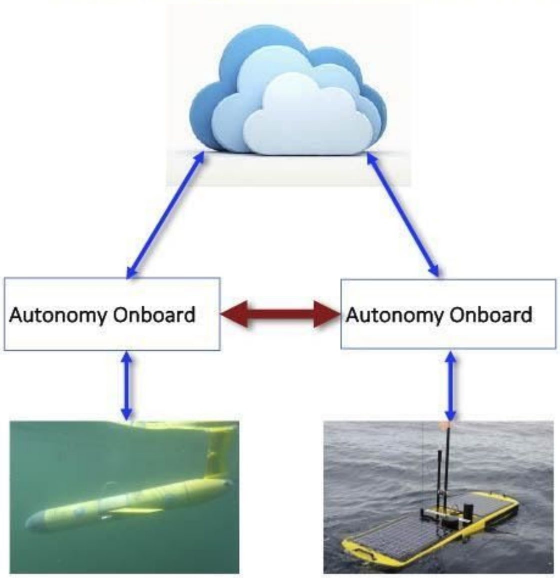
"Marine Robotic Networks: From Plateforms to Services"

-- Fumin Zhang (Georgia Tech) and Catherine Edwards (U Georgia)





Distributed Robotic Network Design



Major Challenges:

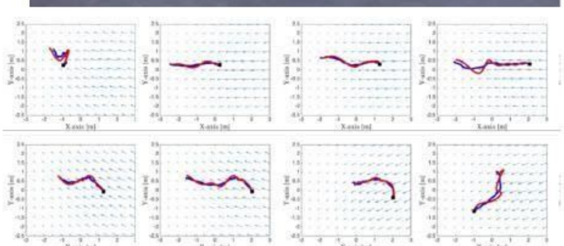
Currently rely on shore-based guidance (not an option in all systems)
Acoustic communication underwater is rarely an option

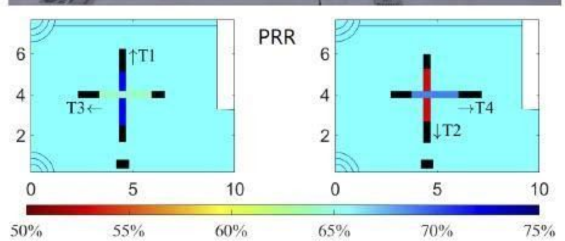
Other Factors:

Eliminate risk at surface
Limitations of onboard processing
When and how to trust onboard decision-making

3

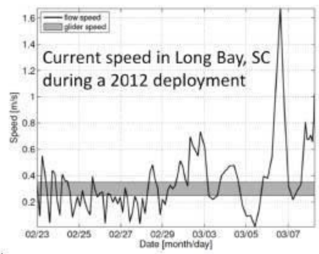
Lab Experiments: Flow and Communication



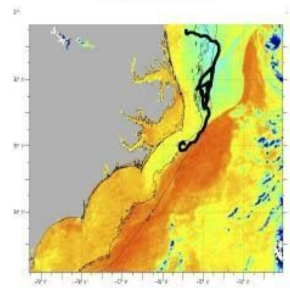


Challenges of Field Experiments

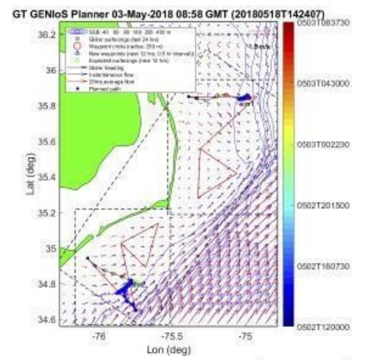
Temporal gradients

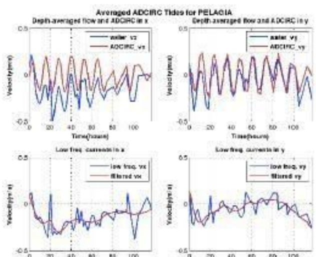


Spatial gradients



Model uncertainty



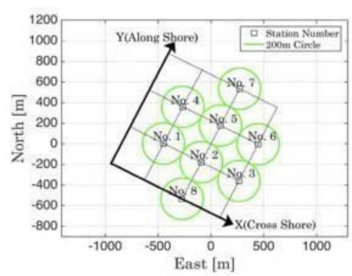


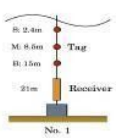
Time delays
"Bioterrorism"

Chang et al., 2015

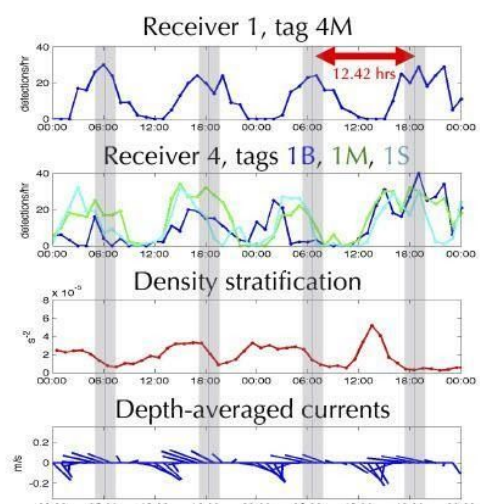
Hou et al., 2018a,b

Challenges of Field Experiments: Acoustics





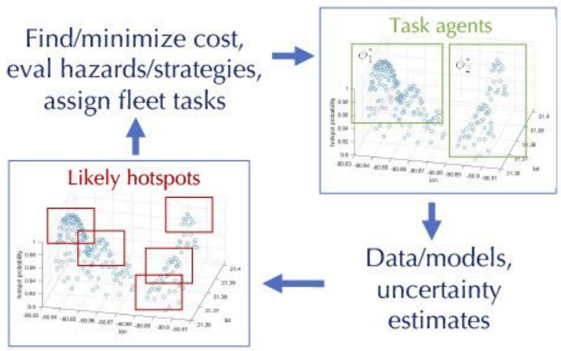
Gray's Reef National Marine Sanctuary, 2014

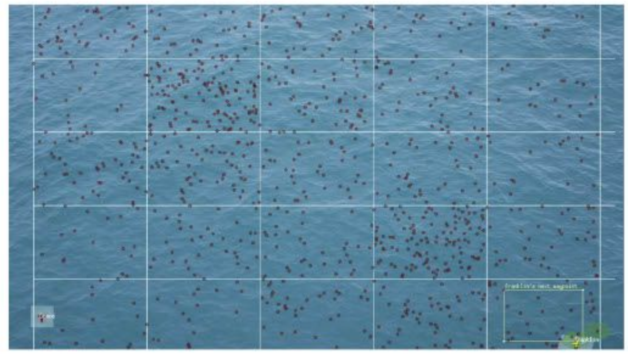


Edwards et al., 2019; Cho et al, 2017a,b → Integrate sensor data for joint modeling/planning

Integrated Robotic Network Design

Goal: Integrate oceanographic and acoustic data/modeling into all levels of network design (path planning, control, AI, symbolic planning) for fisheries management



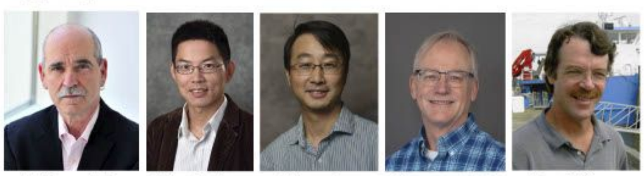


How would system design choices change with availability of:

- reliable long-range wireless comms?
- underwater GPS?
- accurate clocks?

Acknowledgments

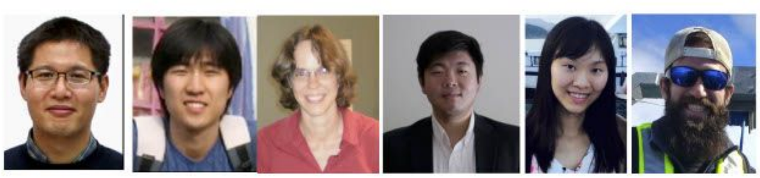
Co-PIs:



Michael Cox, Xiaobo Tan, Aijun Song, Harvey Seim, Jim Nelson

PEACH co-PIs

Graduate Students:



Sungjin Cho, Dongsik Chang, Klimka Szwaykowska, Tony Lin, Menxgue Hou, Frank McQuarrie

CNS-1828678, S&AS-1849228, GCR-1934836, OCE-1032285, OCE-1559476, S&AS-1849137

N00014-19-1-2556
N00014-19-1-2266

FA9550-19-1-0283

N00173-17-1-G001
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NOAA/Navy SanctSound

Appendix D. Workshop Planning Tips

D.1. Instructions for Preparing Lightning Talks

Each session will have a series of pre-recorded 3-minute lightning talks. These talks should contain original contents and answer the questions in this **template** 3-minTalkTemplate.pptx.

- What is your area of expertise?
- What are the challenges in your research/application area?
- How are the challenges related to underwater wireless communications and sensing?
- How do you rate the current state of the art in underwater wireless communications and sensing?
- What are the most critical issues in underwater wireless communication and sensing for the research community to tackle?
- What are the potential environmental and societal impacts of technological advancement?
- What are the opportunities for industry-government-academia collaboration?

The pre-recorded lightening talk will be strictly limited to 3 minutes and the maximum size is 300 MB. Please use the link provided to you to upload your video.

Several tools are available to record your presentation:

Loom: Loom allows you to record your screen, voice, and face and create an instantly shareable video. Instructions on Loom are available here.

Microsoft PowerPoint: You could also record your Voice over PowerPoint presentation and then convert it to MP4

Meeting Software: You could use any meeting software if the video quality is good. Here are some links to instructions on recording a meeting on different platforms:

WebEx: Record a Cisco Webex Meeting
OBS: How to Record a Presentation using OBS Studio-IEEE CPC [YouTube Video]
Skype: How do I record my Skype calls
Google Meet: Google Meet Help
Zoom: Local Recording - Zoom Help Center
GoToMeeting: How to Record a GoToMeeting Session
Microsoft Teams: Record a meeting in Teams - Office Support

D.2. Tips on Moderating an Online Panel

Notes were taken at the online rehearsal for NSF workshop blue-uci2021

Check zoom settings and appearance:

1. Ask all participants to turn their cameras on. Fit all participants' video on one screen so you can see all of them at once;

2. Check your own camera settings and room lighting. If the background is cluttered, use a virtual background. Dress up professionally, at least on the top portion of your body

Some good tutorial videos about how to look good on camera are available here (for guys) or here (for gals).

Be confident with good prep:

1. Demonstrate confidence. We have been using video conferences for more than 9 months now and we are pretty good at it. If you run into technical issues, a student in the room will help you.

2. Hosting a video conference is a little bit more work than face to face conference and how do we do better than a routine job? Short answers: use a slightly faster tempo, call on everyone, and use interesting/debatable/controversial questions.

3. Consider the audience and participants: what are the difficulties they experience? Lack of attention, distractions, getting bored, multitasking. So how to attract attention and keep people engaged? Let's learn from interesting TV shows which use conflicts, controversy, or debate.

Safe options for professional meetings: may not be strong conflicts, but debate questions and different opinions related to the theme of the discussion. Even fake debate can get people excited.

4. Good prep boosts confidence: go over the session talks and the pre-recorded videos. Get to know the people in the session, prepare questions ahead of time, have a couple of people you know in the room to help stimulate discussion.

5. Be conscious that you are in charge: you are managing the time, energy, and attention of everyone in the room. You set up and manage the dynamics of the discussion.

Procedures

1. Introduce all participants: hello to everyone as they join the room. Let everyone introduce themselves, starting the introduction with yourself to set an example, keep it as short as one minute.

This is different from introducing a speaker in the webinar sessions. More on that later. We will have a zoom meeting to exchange information about the attendees.

2. Put out the questions to be discussed by showing them on the screen for a short time, then stop screen sharing so you can see everyone in the discussion panel. You may copy the questions into the Chat Box. Go around the room so everyone gets a chance to speak. May go in different orders for different questions.

For difficult questions/tasks, ask someone you know well to step up first. Ask the keynote speakers or the short-talk speakers as your helper.

3. How to stimulate someone who is shy to speak up? Use specific praises, show interest in their opinion, give them a bit more time, don't force;

4. How to stop someone who rambles on and on or who goes off-topic? Clearly set the time limit for each question per person. Try to maintain the time limit as closely as possible. if someone goes over the limit a lot, acknowledge their opinion by rephrasing what they say (what I hear you say is …, what I understand from you is …), and then say: this is a really interesting question/opinion/problem, and I think it is different from what we are trying to address here (or it would take more time than we have today), so let us focus on …. (or let's move on to the next person).

A tip used by radio interviewers: play a soft music piece or alarm and make it louder if the speaker drags on.

5. Prepare some controversial questions and fake debates. We shall have a zoom meeting to discuss those and ask the NSF PMs for their inputs.

6. Have another person or two to scribe the discussions. Consider asking the student helper to promote you any chat messages if you do not get to those.

Zoom Webinar sessions:

1. How to start the workshop or a session: have someone from NSF address the audience and give opening remarks. Need to nail down names for each session.

2. How to introduce the keynote speakers: treat them as VIPs and formally introduce them before their talks. What is considered a bad introduction? Two extremely bad cases:

a. read the bio word by word – long and boring

b. very short, just a name and a title of the talk may be the affiliation. That's it.

Some good examples are given by the team:

a. Start by saying the name, formal title, and affiliation clearly. (Do not say: so and so does not need an introduction)

b. Highlight the biggest achievement in their career and put it in perspective: The first person to work on x problem, the first to solve y, leading the best xy effort/team, despite the mainstream working on z, he/she insisted on w approach, the best know paper that started a new field of study, the most recent publication that investigates …., NSF career award, professional fellowship (IEEE fellow, ASA fellow, and NAE member, etc).

c. Provide some insights about the speaker that the general public cannot get from google search. Be careful about using their personal hobby that is not related to the profession. Ask the speaker beforehand for permission if you consider sharing those non-professional aspects (soccer player, ballroom dancer, etc.). Scuba diving may be good ☺

d. Be respectful w/o flattering. No “your majesty” or “your honor”, Haha.

D.3. Website Creation and Maintenance

Website creation follows three steps: 1. Finding a website host and data storage space, 2. Selecting a web editing tool and data storage method, 3. Content editing. Some tips and experiences are shared here for future reference and maintenance.

1. Find a website host and data storage space

Firstly, to get the domain name, several web hosts were considered: Lehigh LTS, GoDaddy, and Network Solutions. Lehigh LTS can host a website for this special project with minimum cost, but only under the lehigh.edu domain. The LTS has to take charge of all content editing with Drupal Content Management System which often takes about 24 hours to turn around. A domain name of our choice can be purchased at Network Solutions for $40 /year and a bit less with GoDaddy. Hosting the website will cost additional depending on the services you use.

We selected the Network Solutions Web Hosting for Premium (Hosting-Unix) package with a one-year subscription. The following services are included in this package: the domain name, unlimited disk space, unlimited email boxes, SiteLock Premium (Malware Scanning, Auto Malware Removal: protect the website and mailboxes from malicious attacks), and SSL Certificate (get a website with https:// instead of http:// so the website is considered safe to browse).

The common data storage spaces include Lehigh network drives, google drive, and Dropbox. We would like the data storage space to be easily accessible by multiple users inside and outside of Lehigh University and also allow external users to fill in forms and upload files. To share the video of the pre-recorded lightning talks, we use the Dropbox file request function so that the users can upload their files through a link. Lehigh University provides all students and faculty unlimited Dropbox space for $100/year and a Google Drive space of 15 GB without extra charge. We used both Dropbox and Google Drive to store and share files. All video recordings are also copied to Network Solutions website storage for easy link and access.

2. Selecting a website creation/editing tool

A resource page for website creation and editing tools is provided by Lehigh LTS at https://confluence.cc.lehigh.edu/display/LKB/Website+Creation+and+Tools, where the commonly used tools for non-professional website creation are WordPress, Google Site, and Confluence. The experienced web developer will code a static page with HTML, CSS, Java, and/or Javascript.

HTML makes up the layout and structure for the website; CSS is used to style a website and is used hand in hand with HTML to add colors, backgrounds, layouts, font sizes, and more. This language is a core technology web developers use to design and build websites; Java is an object-oriented programming language used to develop website content, games, apps, and software. Java is used in the production of most Android apps; JavaScript is a lightweight programming language (“scripting language”) used to make web pages interactive.

For the blue-uci 2021 workshop website, we used HTML and CSS, here are some useful tutorial websites for reference:

Our workshop assistant Ms. Chuqi Chen used a text editor to write HTML and CSS codes for the website. Tutorials for HTML and CSS are found here: HTML Tutorial and CSS Tutorial.

To change the content on the website via Network Solutions and a text editor directly, first, log in, and then click "Upload Files (FTP)" under the My Hosting Packages section:

then in the following screen, choose the "File Manager" tab:

and then click the "File Manager" button in the window below:

The file folders will appear and an HTML file may be modified by opening it directly as a text editor.

3. Content editing

The contents of the website are heavily borrowed from the Smart Oceans 2020 workshop website https://smartoceans2020.org whose creators Drs. Fadel Adib of MIT and Josh Anderson of WHOI gave us some insights via a zoom meeting. To avoid creating an interactive website, the registration function was achieved with a link to a Google Form which allows the user to fill in and submit the form. Google forms also collect the information of the attendees and export lists and statistics. We changed the settings of the form and also purchased the upgrade option. An important setting is to uncheck the “Requires sign-in” option, so people do not need to sign in to their Google accounts to access the form as many do not have a google account. To reduce multiple entries from the same user, we also set up an automatic reply to send an email from Google Form and tell the user that the registration has been received. Moreover, before the workshop, we also send emails from Google Forms to the registered attendees with reminders, and the Zoom Webinar meeting ID, and the agenda for the workshop. This feature requires a paid upgrade of $20/mon.

All photos and bios of our invited speakers were taken from websites with no or minimal effort from the speakers. All wordings and appearance were checked by the planning team members to ensure quality and accuracy. Every page was also tested on different web browsers such as Firefox, Google Chrome, Microsoft Edge, and mobile devices. As a future improvement, we may use Go links to shorten the long links to Zoom meeting/Google forms, etc.