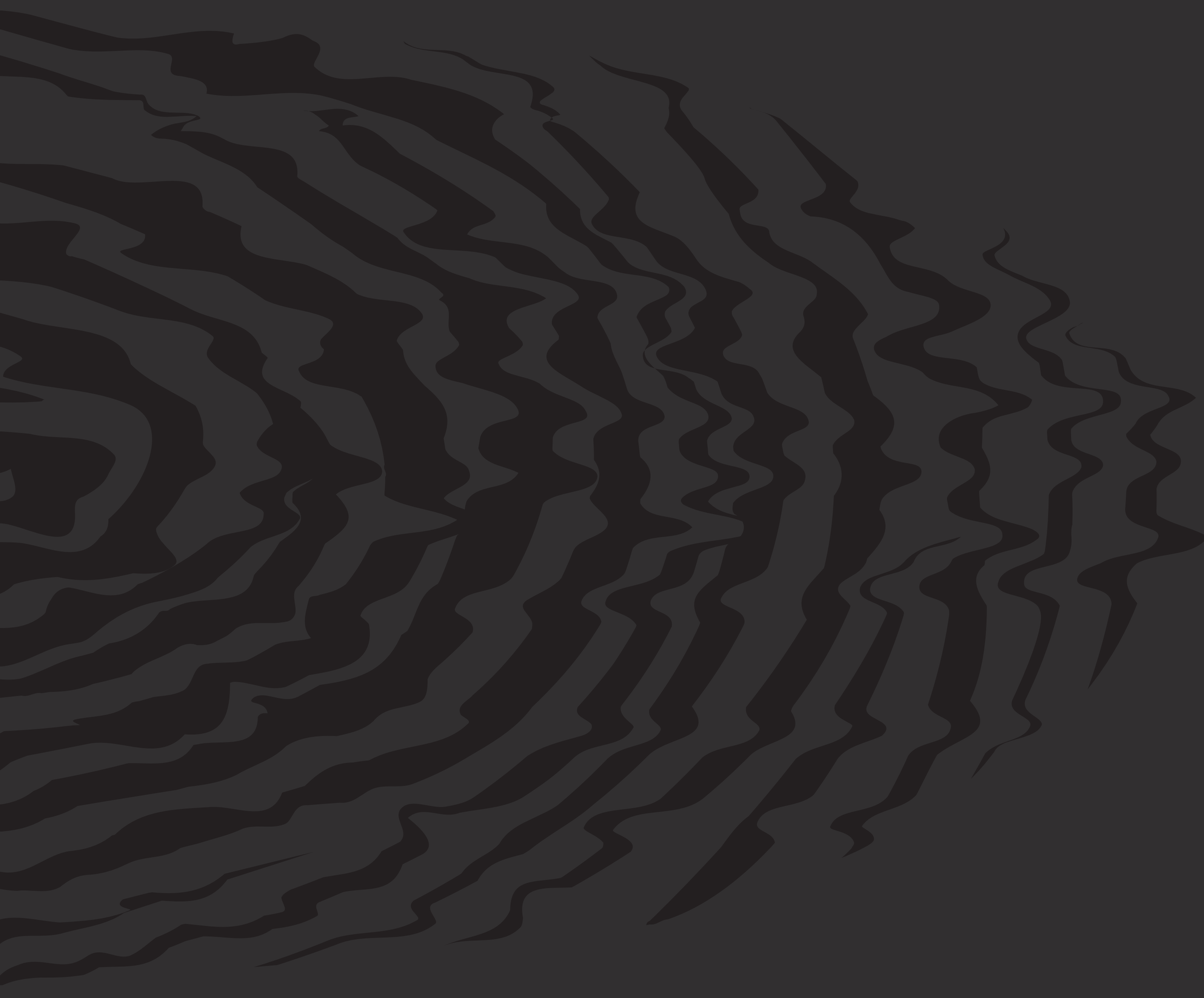
biennial report 2019

Applied Physics Laboratory

UNIVERSITY OF WASHINGTON



apl-uw

Scientific discoveries

Engineering innovations

Solutions for regional, national, and worldwide problems

The Applied Physics Laboratory is a research unit of the University of Washington. We serve as a trusted research and development agent by anticipating broad scientific and engineering challenges and responding quickly to rising national research priorities. Core expertise is in ocean physics and engineering, ocean and medical acoustics, polar science, environmental remote sensing, and signal processing.

Designation by the U.S. Navy as a University Affiliated Research Center requires that APL-UW operate in the public interest. From our integral position within the University of Washington scholarship, research, and innovation enterprise, we apply rigorous scientific inquiry and engineering excellence in pursuit of solutions for the good of our region, nation, and world.

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our legacy and vision

In the summer of 1943 the first scientists and engineers arrived at the newly formed Applied Physics Laboratory on the University of Washington campus in Seattle. They were assembled under the leadership of the Laboratory's founder and first director, Dr. Joseph Henderson, with a mandate to solve an urgent national problem. They had the capabilities, had been provided the assets, and were allowed the freedom to discover the best solution to the problem. They also seized the opportunity to establish a laboratory where unforeseen future problems could be addressed, drawing on their collective expertise and the resources of the University. So began the Applied Physics Laboratory of the University of Washington.

THREE-DIMENSIONAL UNDERWATER ACOUSTIC TRACKING RANGE INSTALLATION, MARCH 1960.

Through the dedication of the Laboratory and University communities over the decades, APL-UW has evolved into a world-renowned center of excellence in scientific and engineering research and development. Our research portfolio blends and balances the fundamental research priorities of national, state, and private agencies with the applied science and technology priorities of industry and Department of Defense agencies. Designation by the U.S. Navy as a University Affiliated Research Center (UARC) requires that APL-UW operate in the public interest. Our research sponsors count on us to respond quickly to their changing needs and trust that APL-UW will deliver science-based knowledge and applied technologies.

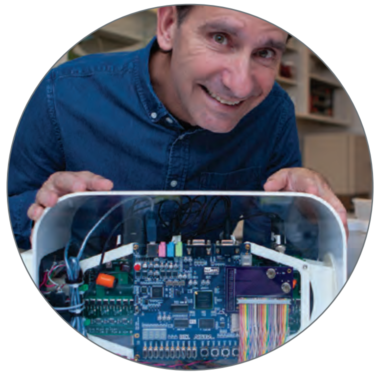
Our scientists and engineers are renowned for their ability to field ambitious research programs, particularly in ocean environments, and for their successful transition of fundamental scientific discoveries to applied projects that deliver knowledge and products to the Navy, government, academia, industry, and the public to enhance the nation's defense, safety, health, and prosperity.

The freedom of inquiry at the core of our operational philosophy has fostered a wide spectrum of capabilities. Expertise spans ocean physics and engineering, ocean and medical acoustics, polar science, environmental remote sensing, and signal processing. This breadth readies us to meet the challenges ahead, where multidisciplinary strategies and collaborative teams will be essential. Our ability to meet future needs is enhanced by our close partnerships with UW colleagues and collaborations with scientists and engineers across the nation and world.

This **Biennial Report** presents highlights of the Laboratory's expertise and contributions to science, scholarship, and technology innovation. They show that our programs make observations spanning time and space scales from billionths of a second to decades and from the subcellular level inside the human body to entire ocean basins. These examples illustrate that our success often relies on combining scientific expertise with cutting-edge engineering, and advancing basic research to applied technology development.

We envision that 75 years from now scientists and engineers will join APL-UW ready to address our nation's greatest challenges. As the current stewards of the Laboratory's legacy and welfare, our goal is to ensure they have the assets they need and are allowed the freedom to use their abilities to discover solutions to those future problems.

– apl-uw leadership



apl-uw celebrates 75 years

In 2018 APL-UW celebrated its 75th anniversary. At the recognition ceremony on 27 July, honored speakers included Director Emeritus Robert Spindel, UW Provost Mark Richards, CDR Robert Patchin, and U.S. Representative to Washington District 1 Suzan DelBene. The event was attended by current and retired APL-UW staff, University of Washington leadership and colleagues, elected officials, and members of the U.S. Navy, our founding and principal research partner since 1943. Speakers recalled the Laboratory's earliest days and charted decades of achievements.

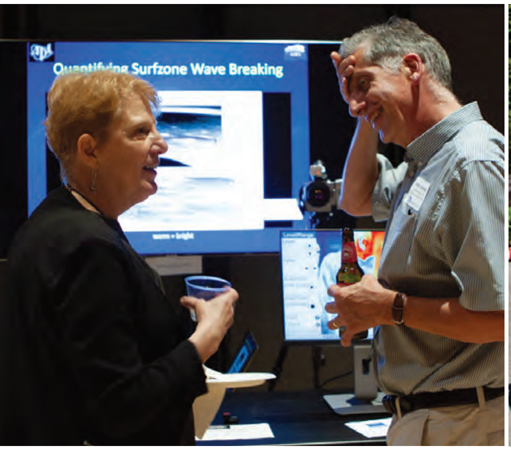
> ***This nexus of academia, government, the public interest, and defense research is enormously healthy and beneficial for the country.***
>
> – University of Washington Provost Mark Richards

The Laboratory was founded during WWII as part of the need to mobilize the academic community to support the war effort. The new Laboratory's specific mission, under its first director Dr. Joseph Henderson, was to develop an effective torpedo exploder that would sense when the torpedo was within optimal range of its target and then initiate detonation. The influence exploder developed in the last months of 1943 at APL-UW was the basis for weapons technologies in the decades that followed.

After the war, APL-UW initiated oceanographic research programs to provide basic physical understanding of how variations in the ocean environment affect the performance of Navy systems. Underwater acoustic tracking ranges were developed for weapons testing and for ship and submarine sensor system alignment. Acoustic studies were undertaken to improve the performance of sonar systems.

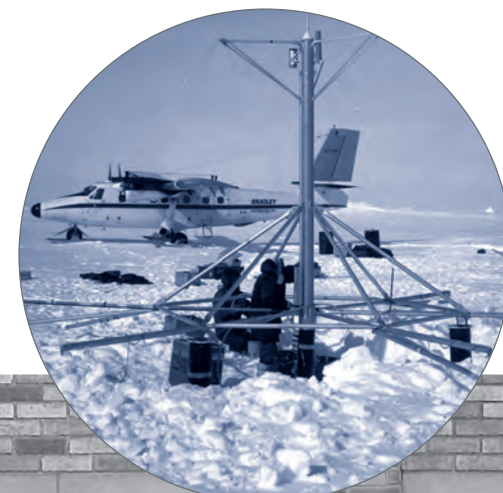
Developing underwater systems imbued APL-UW with engineering expertise that resulted in the design of dozens of specialized research instruments to measure ocean temperature and currents, ice thickness, turbulence, heat content, and much more. A notable first was the development of an autonomous self-propelled undersea research vehicle. It is a remarkable achievement to be first with a technology that is now so important for oceanographic research and naval operations.

> ***APL-UW scientists and engineers have always been driven by what is inspiring, compelling, and ultimately, important.***
>
> – APL-UW Executive Director Lisa Zurk



Throughout our history, APL-UW's research efforts have aligned with national goals. Our portfolio now spans national defense, the environment, human health, and renewable energy. The group that has built underwater tracking ranges for the Navy is now engineering systems for cabled ocean observatories that provide to scientists and the public a continuous, long-term portal to the deep ocean. Some of the specialists in underwater acoustics transitioned their tools and expertise to acoustics in the human body, and now develop medical ultrasound therapies. APL-UW's biological oceanographers are discovering how physical and biological systems are coupled in the marine environment and impacted by a changing climate. And mechanical engineers are innovating marine renewable energy technologies that will someday power Navy installations and over-the-horizon instruments and sensors.

APL-UW scientists and engineers have always been driven by what is inspiring, compelling, and ultimately, important. This is the Laboratory's legacy, which provides a solid foundation for future success.



The Laboratory's unmatched experience and remarkable ability to shift gears and meet new challenges have prepared it to solve problems not yet recognized and ensure that APL-UW will help solve them for the next 75 years.

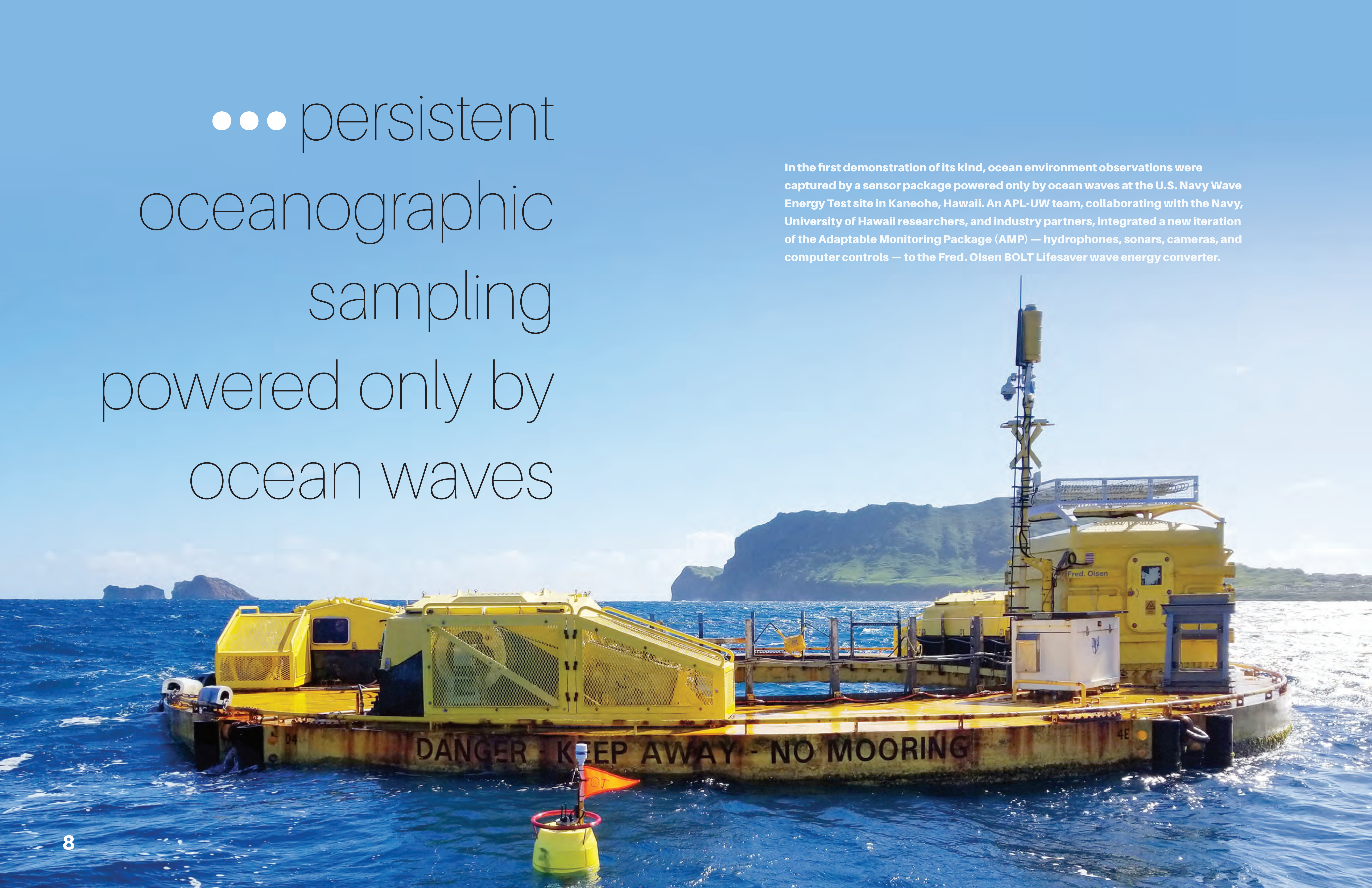
– APL-UW Director Emeritus Robert Spindel

APPLIED PHYSICS LABORATORY UNIVERSITY OF WASHINGTON STAFF, JULY 1945

FOUNDER AND FIRST DIRECTOR DR. JOSEPH HENDERSON, STANDING FAR RIGHT

••• persistent oceanographic sampling powered only by ocean waves

In the first demonstration of its kind, ocean environment observations were captured by a sensor package powered only by ocean waves at the U.S. Navy Wave Energy Test site in Kaneohe, Hawaii. An APL-UW team, collaborating with the Navy, University of Hawaii researchers, and industry partners, integrated a new iteration of the Adaptable Monitoring Package (AMP) — hydrophones, sonars, cameras, and computer controls — to the Fred. Olsen BOLT Lifesaver wave energy converter.



WAMP — the wave-powered adaptable monitoring package

The AMP is an integrated instrumentation system, developed to monitor the environment around marine energy conversion devices. These are new technologies in the burgeoning marine renewable energy sector, so there are concerns about marine ecosystem impacts, especially adverse interactions between marine animals and energy conversion devices. No individual instrument can monitor all types of animals and their behavior. For the deployment offshore Hawaii, AMP was configured with a multibeam sonar, acoustic camera, two hydrophones, and two optical cameras for stereo vision, along with eight strobe lights and wipers on all the optical components to keep them clear of biofouling.

Collaborative research and development on AMP among APL-UW, the University of Washington Department of Mechanical Engineering, and industry partners has been ongoing since 2012. Senior Engineer James Joslin, who began working on the project as a graduate student, explains that the AMP has gone through three generations. The first was to develop the hardware and put all the instruments into a single body, and the second concentrated on software enhancements. That is, how do you run the instruments over time without crosstalk interference? And for the third, current generation, the team is focused on smart data control and processing — developing algorithms to do automatic target detection, tracking, and classification.

At the Wave Energy Test site in Kaneohe, the U.S. Navy must understand the risk of interactions between energy conversion devices and marine mammals, especially humpback whales that inhabit the area every winter. The Lifesaver wave energy converter has three cables anchoring it to the bottom. They are tensioned by power takeoff generators and as the buoy rolls on the waves the motion is converted to electricity. If whales are in the area, could they become entangled in the cables? Though this may be a low-probability event, it has a significant adverse outcome if it occurs. Joslin adds, "If you are looking for a rare event, you have to be looking continuously."

AMP's persistent eyes and ears work together to detect a target. Hydrophone and sonar data are processed, and if an event meets the detection algorithm's threshold, AMP tracks the target, and if the track is long enough, lights are switched on, and cameras capture images. In post-processing a target classification algorithm determines whether the target is of interest. That is, is it an organism or just, for example, bubbles injected from breaking surface waves or a piece of floating kelp? These smart self-controls also limit AMP's data load. If all sensor data were recorded continuously, terabytes would be collected every day, most absent any events of interest.

Previous iterations of the AMP were powered by a cable from shore, or by onboard batteries. The first package was flown to a bottom docking station by remotely operated vehicle, and others were configured as landers and lowered from a vessel to the seafloor. For the deployment at the Wave Energy Test Site, Mechanical Engineer Paul Gibbs was challenged to configure the sensors and control components into a form factor that could slide through a small hole in the Lifesaver deck and project underneath it in an energetic wave environment. Over the six months at sea, the WAMP sensors and computer controls collecting and processing observational data were drawing about 500 watts of power from the BOLT Lifesaver — the equivalent of 10 car batteries per day. This integration was robust: while the Lifesaver was generating power, WAMP was operational 85% of the time, nearly matching the performance of previous AMP deployments powered by a cable from shore.

The WAMP deployment in Hawaii also provided the engineering team an opportunity to test a prototype autonomous undersea vehicle docking station that uses wireless power transfer through the seawater to recharge a vehicle's batteries. "We partnered with a local, UW spinoff company, WiBotic, and developed an underwater housing for their system," says Joslin. In this demonstration of wireless power transfer, there was a seawater gap of about 1 cm between the transmitter and receiver, and over the course of six months, there was no degradation in the signal strength, even with significant biofouling.

The primary goal for APL-UW researchers was to investigate the potential animal interactions with a commercial wave energy device, and in so doing, they demonstrated an ability to make persistent ocean observations powered by the ocean environment itself. They also took a step further — showing how marine renewable energy can be harnessed to power autonomous robotic systems, potentially expanding the spatial range of observations. One of the most satisfying outcomes for the team was the successful collaboration among the Laboratory, U.S. Navy, Fred. Olsen, and WiBotic. Separately, all had components under active development and on this occasion brought them together to create transformational new capabilities for ocean sensing and exploration.

MarineSitu

The core technology of the AMP includes the hardware and software backbone that integrates up to 10 instruments into a single marine observational node that may be configured to address a wide range of monitoring objectives. In 2016 MarineSitu was spun off with support from CoMotion — the University of Washington's innovation hub that guides researchers and inventors to license intellectual property, identify funding and investor opportunities, and start up new companies. Commercializing this technology will reduce the cost and barriers of marine monitoring to meet regulatory standards, and will make these capabilities broadly available to the maritime industry market.

team members: ROB CAVAGNARO, PAUL GIBBS, JAMES JOSLIN, AARON MARBURG, MITCHELL SCOTT, ANDREW STEWART (APL-UW); EMMA COTTER, COREY CRISP, PAUL MURPHY, BRIAN POLAGYE (UW Mechanical Engineering); MATT CARLSON, BENJAMIN WATERS (WiBotic); PAT CROSS (University of Hawaii); PATRICK ANDERSON, ANDREW ROCHELEAU (Sea Engineering Inc.); EVEN HJETLAND, JONAS SJOLTE (Fred. Olsen Ltd.)

sponsors: U.S. NAVY, DEPARTMENT OF ENERGY, NATIONAL SCIENCE FOUNDATION, UNIVERSITY OF HAWAII

clearing seafloor hazards from coastal areas

Throughout the summer of 2019, an APL-UW team aboard the R/V *Jack Robertson* put the Multi-Sensor Towbody (MuST) through a series of tests. Deployed from the vessel's A-frame, MuST flies underwater searching for potentially hazardous objects on the bottom or buried in the sediment with acoustic sensing technologies. Attached to the vessel by a fiber optic, two-way communications and control cable, MuST sonar data stream to acquisition, display, and analysis computer systems aboard the *Robertson*, giving operators a real-time map of the bottom as they pilot the vessel in a lawnmower pattern over the survey area.

the unexploded ordnance problem

Munitions, left behind from past military training and weapons testing activities, litter shallow water environments at many hundreds of current and former Department of Defense sites encompassing millions of acres. The U.S. Army Corps of Engineers and the U.S. Navy have identified more than 400 underwater sites that are potentially contaminated with unexploded ordnance (UXO), where they pose a threat to human safety and the environment. "Congress mandated that the DoD remediate these areas of hazards and give the lands back to the citizens of the United States," says Principal Investigator Kevin Williams. "To do that, they need the tools to find and clear all UXO in these shallow water areas."

Funded by the Strategic Environmental Research and Development Program (SERDP) and Environmental Security Technology Certification Program (ESTCP), both focused on developing sensors, systems, and platforms to remediate this UXO problem, APL-UW designed, built, and is now field testing the MuST.

key industry partners

The underwater MuST components include the FOCUS-3 towbody, manufactured by MacArtney Underwater Technology, onto which are mounted two sonar systems. A handling system for the towbody, and the data acquisition and analysis hardware and software are on the surface vessel. Placing these systems on the vessel reduces the number and complexity of in-water components.

Off-the-shelf side scan sonars send out fan-shaped beams that sonify the bottom; the received scatter is transformed into maps of the seafloor and images of objects resting on the sediment–water interface. A specialized, one-of-a-kind, three-dimensional, sub-bottom profiler, manufactured by EdgeTech, uses a broadband acoustic pulse to illuminate and then see buried objects. "EdgeTech had a sonar system that was designed to look into sediments and APL-UW had the engineering expertise to integrate the sonar into the towbody platform and improve the image processing," remarks Williams. Together, the sonars can image the top 1–2 m of the sediment with a resolution of 10 x 10 x 10 cm and image the sediment–water interface at sub-centimeter precision.

detect and geolocate

Field tests on Lake Washington simulate operational parameters, where the MuST surveys an area of one to several square kilometers in water depths of 5 to 40 m. As the vessel covers the survey area in a lawnmower pattern, sonar data are passed along the high-power, wide bandwidth tow cable. Aboard, detections of potential UXO targets will be made available to the operator and these regions of interest logged for further scrutiny.

To achieve the goal of locating logged objects to within 2 m in absolute Earth coordinates requires careful coordination between the towbody, its sensors, and several systems aboard the vessel. During a survey, the vessel position and heading, tow vehicle depth, and cable length from the tow arm to the vehicle are recorded continuously. An inertial navigation system corrects the sonar data and maintains an estimate of where the towbody is underwater. A GPS sensor mounted near the top of the MuST acquires location fixes when it is on the surface, and when it dives uses that fix and heading as an initialization to estimate its location as it flies underwater at controlled altitudes above the bottom.

from fundamental physics to applied engineering

How does the operator decide that objects of interest are indeed UXOs, and not something more benign? Classification tasks performed with the MuST sonar data will leverage capabilities developed by APL-UW physicists over the past decade. They have fielded many experiments to understand how sonars respond to UXOs resting on the seafloor or buried in sediments in coastal environments. Studies began by characterizing acoustic scattering from mine-like targets at short range in the Naval Surface Warfare Center test pond, with its pristine, controlled conditions. Experiments progressed to the Gulf of Mexico off Panama City, Florida, where acoustic sources and receivers were mounted to a rail system about half the length of a football field that moved along the seafloor interrogating targets including simulated UXOs. Through iteration, APL-UW physicists built an understanding of target acoustic scattering, the effects of the seabed on target scattering, how to detect and classify buried objects, and how to make classification decisions in areas with a great deal of acoustic clutter.

An important discovery was that certain characteristic features are present for each UXO target type. Mid-frequency sound creates resonances in the target; sound not only bounces off, it excites the target volume to ring. Acoustic scattering models were then developed and tested using the experimental data gathered at various ranges, grazing angles, burial depths, and environmental clutter scenarios. These characteristic resonances are part of the acoustic fingerprints of UXOs and will be used by the onboard data analysis systems to help make classification decisions during the MuST operations.

APL-UW's great strength is the integration of fundamental scientific research and applied technology development under one roof. This results in knowledge transfer to academia and the government, and generates technologies that are useful to government sponsors and industry. The problem of UXO remediation required understanding the physics of acoustic scattering from targets. Once researchers had demonstrated detection and classification capabilities to program sponsors, they addressed the need to package the sensing and signal processing technologies on mobile platforms. Williams reflects, saying, "It's taken 12 years to get from basic research on target physics to a piece of equipment that has promise of being viable commercially." MuST field tests continue through late 2019, moving to a simulated target field in an ocean environment.

team members: PAUL AGUILAR, BEN BRAND, MIKE KENNEY, MATTHEW LINQUIST, TIM MARSTON, TIM MCGINNIS, NICK MICHEL-HART, DANIEL PLOTNICK (APL-UW); NICK LESNIKOWSKI (David Evans and Assoc.); KEVIN RYCHERT (EdgeTech)

sponsors: STRATEGIC ENVIRONMENTAL RESEARCH AND DEVELOPMENT PROGRAM, ENVIRONMENTAL SECURITY TECHNOLOGY CERTIFICATION PROGRAM

> *"Our goal is to look into the sediment. Many sonar systems can show you what's lying on the bottom. The MuST system images buried targets and tells us something about their properties, too, which is novel."*
>
> – Kevin Williams

ultrasound technology advances individualized medicine

A new device that uses an array of ultrasound transducers speeds the search for disease biomarkers and tests of drug efficacy. Developed in a collaboration among researchers at the Laboratory's Center for Industrial and Medical Ultrasound and the UW School of Medicine, the invention has promise to be a transformational advance in pursuit of individualized medicine treatments for cancer, heart, and kidney patients.

PIXUL LAB PROTOTYPE (LEFT) AND COMMERCIAL DEVICE (RIGHT)

innovation imperative: the need for a 'simple' solution

Many of the most widespread diseases have an epigenetic component. That is, they are caused by the abnormal expression of genes, not an alteration in the genetic code itself. And unlike genetic problems, epigenetic disease can be reversed pharmacologically.

Researchers, clinical labs, and pharmaceutical companies search for epigenetic alterations and their genome-associated proteins using chromatin immunoprecipitation (ChIP) methods. And while ChIP assays have become faster and more sensitive, the preparation of cell cultures for assay remains a major bottleneck, gobbling up to 80% or more of a research lab's time.

Before running a ChIP assay, researchers must grow and harvest cell samples, then shear the samples' chromatin — the material making up chromosomes — using the power of ultrasonic cavitation. Thomas Matula, Director of CIMU, recalls when he was first approached by Dr. Karol Bomsztyk of UW Medicine. "Karol came to me looking for a way to break down DNA. But instead of treating one cell sample in one vial with ultrasound, as is standard practice, he wanted to treat every sample in a 96-well microplate simultaneously." Achieving this goal would conquer the bottleneck of sample preparation and speed discovery. Whereas cells had been grown in culture plates, harvested and placed in vials, then sonicated, and finally transferred to a 96-well microplate for the ChIP assay, Dr. Bomsztyk envisioned all these steps completed with no transfer of material and no moving parts.

"Karol needed to shear chromatin into random, tight distributions of only hundreds of base pairs. We had never worked on ultrasound physics at subcellular levels," says Matula. The vessel itself, a standard, low-cost, 96-well, plastic microplate, also proved challenging because it is lossy, dissipating ultrasound energy. CIMU engineers Brian MacConaghy and Adam Maxwell first put a large transducer under the microplate to generate a lot of cavitation. It worked, but it was too inefficient to develop further into a lab instrument. That's when they arrived at the solution of 'pixelated' ultrasound — PIXUL, where miniature transducers focus equal amounts of energy into every 96-well independently, generating the shearing energy required to treat all microplate wells within minutes.

pixelated ultrasound — PIXUL

The resulting device is a transducer lens assembly that focuses ultrasound into every well of the microplate, a high-power amplifier to drive the transducer array, a Peltier cooling system to reduce heating and degradation of cell samples, and computer control of the ultrasound pulse parameters — number of cycles, treatment configuration, and treatment time. PIXUL is easy to use. And because sonication is fast, disease biomarkers are preserved and assay findings are more accurate. PIXUL yields more sheared chromatin than other protocols that rely on the manual harvest of cells and transfer to tubes for sonication. And chromatin fragmentation into random, tight distributions is more consistent with PIXUL than with other devices that require individual tubes and sample transfers, thus improving assay sensitivity and resolution.

toward individualized medicine

Epigenetic therapy is one of the fastest growing areas of disease treatment, especially in cancer. "However, epigenetic therapy has been empirical rather than rational," notes Dr. Bomsztyk. "Meaning, if a patient is diagnosed with a particular cancer, the doctor knows there is a particular treatment that may help, but it doesn't tell the doctor which patient will and which will not respond to the treatment." The ability to search for and identify biomarkers quickly and with high throughput will provide physicians the guidance needed to tailor individualized treatments. Matula sums up the motivation for PIXUL saying, "We have invented a technology that will prepare cell samples in minutes so that researchers can spend valuable time and resources on assays, allowing them to make biomarker discoveries and test drug efficacy at orders of magnitude faster."

from idea to impact

A patent application: "Ultrasound system for shearing cellular material," describes PIXUL's capability to process biological material with an array of transducer elements that are positioned to align with sample wells in a microplate. Drs. Bomsztyk and Matula are co-founders of Matchstick Technologies, Inc., a startup company that has licensed PIXUL technology from the University of Washington. Matchstick will manufacture PIXUL instruments for Active Motif, a global epigenetics company, that will market and speed delivery of PIXUL devices to end users.

team members: BRIAN MACCONAGHY, THOMAS MATULA, ADAM MAXWELL (APL-UW); KAROL BOMSZTYK (UW Medicine),

sponsors: NATIONAL INSTITUTES OF HEALTH, WASHINGTON STATE LIFE SCIENCES DISCOVERY FUND, ACTIVE MOTIF

> ***"I now use a PIXUL prototype in my lab every day."***
>
> – Karol Bomsztyk

PIXUL is a fast and easy-to-use device that advances research into epigenetic processes in health and disease, and facilitates screening of epigenetic drugs.

global reach and influence

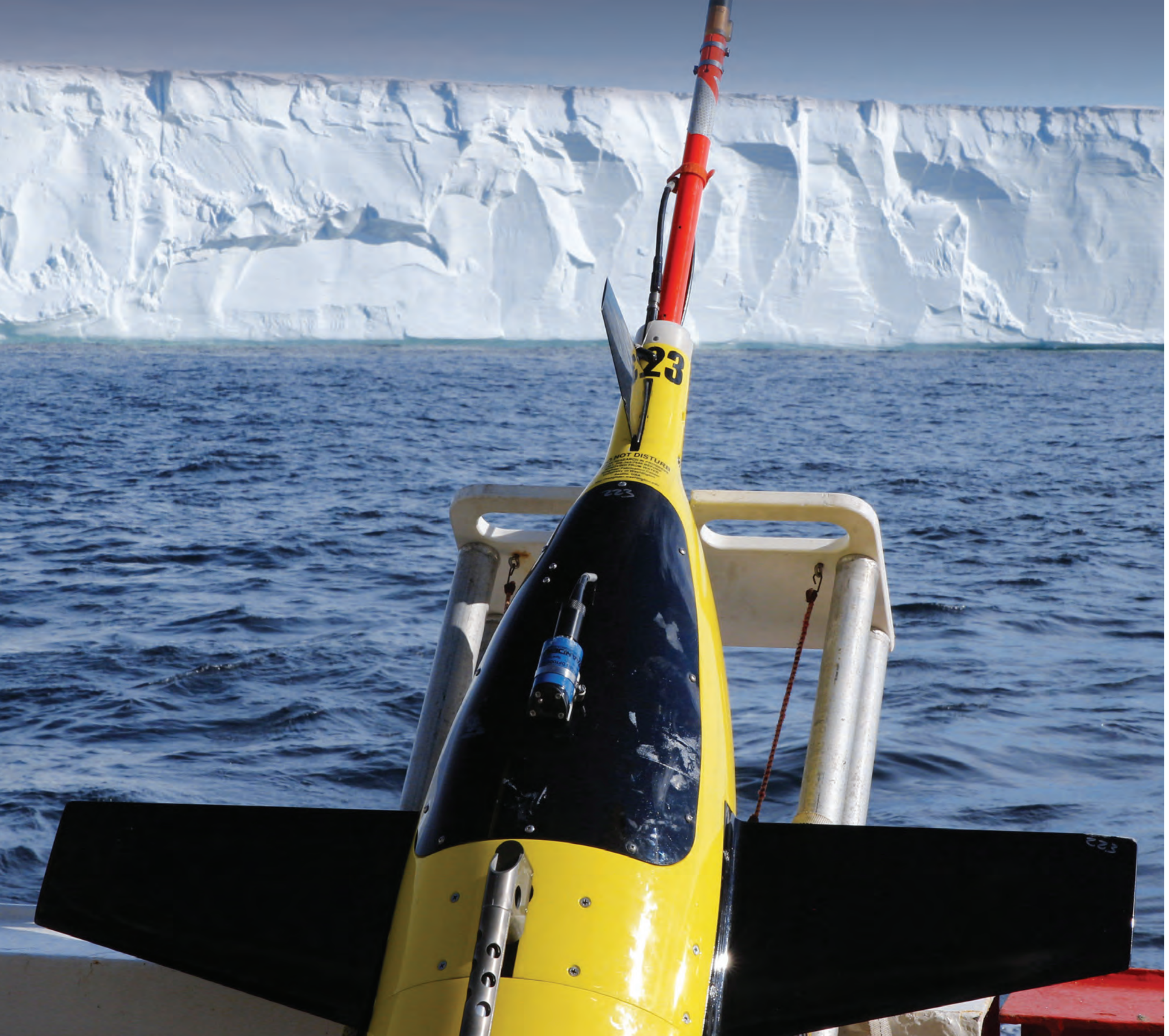
Collaborative research takes us around the world every year.

Stratified Ocean Dynamics of the Arctic
Shelf Break Upwelling and Upper Trophic Level Ecology
Bering Strait Ocean Observing System: Pacific Inflow to the Arctic
Microstructure of Ice Salinity and Temperature
International Arctic Buoy Programme Arctic Observing Experiments
Arctic Domain Awareness

Base map: NASA/Goddard Space Flight Center Scientific Visualization Studio. The Blue Marble Next Generation data is courtesy of Reto Stockli (NASA/GSFC) and NASA's Earth Observatory. The Blue Marble data is courtesy of Reto Stockli (NASA/GSFC).

robotic exploration beneath ice shelves

APL-UW scientists and their research partners launched a small fleet of ocean robots to collect oceanographic measurements for an entire year beneath the Dotson Ice Shelf.



The floating ice shelves that ring Antarctica buttress the inland ice sheet. They are, however, vulnerable to accelerated melting from below by the relatively warm ocean waters that circulate on the continental shelf. As the ice shelves thin and weaken, the grounded ice behind them destabilizes, accelerating flow, melt, and eventual ice sheet collapse. To advance understanding of ocean–ice shelf interactions and, ultimately, improve predictions of ice sheet loss and sea level rise, it is imperative to overcome the challenges of collecting measurements in the ocean cavities beneath ice shelves. During austral summer in January 2018, the team deployed three moorings equipped with acoustic navigation beacons and then launched the robots from the Korean icebreaking research vessel *Araon* off the ice shelf face.

Autonomous undersea vehicles and robotic profiling floats have revolutionized ocean observing, enabling measurements at time and space scales that were previously impossible. APL-UW researchers have leveraged their expertise with these robotic technologies to explore polar oceans over the last decade with great success. In ice-covered seas, where they are denied the surface and the ability to establish a satellite communications and navigation link, the robots must navigate using signals from underwater acoustic beacons.

When planning this high-risk, high-reward mission, the team was motivated by the potential for long-term oceanographic sampling beneath ice shelves, but the irregular, deep cavities posed greater challenges than ever before encountered. Could floats and gliders navigate the complicated cavity geometries? What currents might they encounter? And how would the acoustic navigation signals propagate through the environment?

Four EM-APEX floats — Teledyne Webb Research floats augmented with an APL-UW electromagnetic sensing and processing subsystem — were inserted into a current that carried them into, and eventually through, the ice shelf cavity, allowing them to collect measurements along the path taken by warm, inflowing waters, and documenting their interactions with the ice shelf above. Three floats profiled along the entire circulation pathway, eventually being carried out from under the shelf and into open water with the outflow.

Three long-endurance Seagliders — a small, low-power, buoyancy-driven vehicle developed by APL-UW and the UW School of Oceanography — flew repeated sections across the front of the ice shelf and deep into the cavity interior. Seagliders completed 30 sections across the ice shelf face and 18 surveys of increasing length and complexity within the cavity interior. The most extensive of the interior surveys totaled 240 km of transit under the ice shelf and penetrated over 60 km into the cavity from the shelf face.

photo: Alex Moji

The team fulfilled all the project's objectives: survey an ice shelf cavity, sample the entire undershelf circulation pathway, demonstrate the utility of mid-frequency acoustic navigation for autonomous platforms in this complex acoustic environment, and maintain a persistent presence to sample a full annual time series under an Antarctic ice shelf.

Mission data, relayed to researchers by satellite when the floats and gliders could surface in open water, promise to open several avenues for scientific analyses.

team members: JAMES GIRTON, JASON GOBAT, CRAIG LEE, LUC RAINVILLE (APL-UW); KNUT CHRISTIANSON (UW Earth and Space Sciences); PIERRE DUTRIEUX (Columbia University)

sponsor: PAUL G. ALLEN FAMILY FOUNDATION

••• operating, maintaining, and enhancing the world's largest ocean observatory

APL-UW engineering expertise was integral to the design and installation of the Ocean Observatories Initiative Cabled Array (OOI-CA) beginning in 2009. Since the commissioning of the world's largest undersea observatory in 2015, Laboratory engineers have been principal partners in OOI-CA ongoing operations, maintenance, and enhancements.

Last year, the National Science Foundation extended its support, awarding a 5-year contract to a coalition of academic and oceanographic research organizations, including APL-UW and the University of Washington School of Oceanography, to operate and maintain the network. This high-power and wide bandwidth communications network now hosts more than 150 science instruments and stretches hundreds of miles offshore Oregon, observing deep and coastal ocean processes, seismic activity, a seafloor volcano, and hydrothermal vents. Being 'plugged into' this expansive ocean volume 24/7/365 is transforming how we imagine ocean science and engineering.

daily operations

To ensure the ongoing health of this complex and vast undersea network, engineers monitor, control, and command primary and secondary infrastructure, nodes, and instruments. Mike Harrington, OOI-CA Chief Engineer and director of the Laboratory's Electronic and Photonic Systems Department, passes real-time displays of science and engineering data every time he walks through his office door. From his office computer and a secure Internet connection, he can access the hundreds of dashboards that visualize and control the network and its infrastructure. Harrington watches, for example, measured values of pressure, salinity, and dissolved oxygen from a shallow profiler mooring stream across the computer screen, as well as the mechanical status of its winch that controls the rise and descent of a science pod every day. "We wrote the software that displays these data in real time. It's not only data visualization though, it also gives us an immediate diagnostic that the instruments and the networks connecting them to the Internet are up and running," explains Harrington.

If something goes wrong anywhere on the Cabled Array network, the first notification is usually an email alert. Every minute, every node of the network is pinged. If it does not respond, the system emails Harrington and others. Most troubleshooting scenarios are resolved by addressing an issue with the power supply or by re-establishing the node's Internet connection. As needed, engineers can also send software updates down to the level of individual instruments. To resolve thorny problems as they occur, a science and engineering team will gather at the Operations Center, housed in the UW School of Oceanography. The center is a critical resource during intensive at-sea maintenance operations as instruments are being retrieved and replaced, requiring carefully coordinated power and communications management.

Daily operations have run smoothly for nearly five years. An ongoing challenge is to accommodate the needs of project scientists, who are adding several new instruments — many of which have never before been deployed on an undersea observatory — to the Cabled Array each year. "APL-UW engineers begin working with the scientists at least a year in advance of deployment, testing the instruments in our labs and ensuring they can be integrated with the network," adds Harrington. Software engineers create new dashboards to monitor and control the instrument additions. With its two-way communications, continuous monitoring and operational control, as well as extensive collocated measurements, the OOI-CA is an ideal test bed to support new sensing technologies.

annual maintenance

Every summer scientists, engineers, and students embark on an intensive maintenance cruise aboard a global class research vessel with remotely operated vehicle (ROV) support. The 44-day VISIONS'19 expedition to service OOI-CA network components set sail on the R/V *Atlantis* from Newport, Oregon, in early June. In total, over 100 instruments were brought up from the seafloor and replacements taken back down and plugged into the Cabled Array.

Steaming 300 miles offshore to the underwater volcano at Axial Seamount, the first goal of VISIONS'19 was to replace a shallow water profiler mooring. "This year's cruise involved at-sea support from 16 APL-UW engineers working closely with investigators from the UW School of Oceanography," Harrington recalls. "It was also the first replacement of a shallow water profiler mooring anchored in 3000 m of water. A full year of detailed planning, coordination, and preparation were needed to perform this complicated operation smoothly and safely."

Laboratory engineers designed and installed shallow and deep profiling moorings — three of each — that use winched science pods and instrumented wire crawlers to probe physical, biological, and chemical processes from the seafloor to near surface depths. Unfortunately, during maintenance operations in 2018, a critical wet mate cable connector was damaged on the shallow profiler at Axial. This connector bridges the backbone seafloor power and communications supply to the 12-foot diameter, 7-ton platform moored at 200 m below the surface that supports a winched science pod — itself a heavily instrumented platform that makes daily excursions through the water column to a fixed depth near the surface.

Upon arrival at Axial Seamount, APL-UW engineers began the carefully staged recovery of the mooring platform. All the work had to be completed during daylight hours on three consecutive days; good weather was necessary and there would only be this one opportunity to get the job done during the VISIONS'19 expedition. After triggering acoustic releases, they watched as the platform floated to the surface. They recovered it to the deck and then brought aboard the attached electro-optical cable, from which they had to remove by hand all 84 football floats that stabilize the cable between the anchor sitting 3000 m below the surface and the moored platform.

The next day a replacement wet mate connector and platform were readied on deck. Day three was devoted to redeployment by reversing the recovery effort. Operations came to a tense, but successful, end when the ship was positioned precisely so that the replacement anchor would drop near the initial anchor position. Hitting this mark 3000 m below the ship was critical because the length of cable on the bottom to reconnect the shallow profiler mooring to the array's backbone power and communications supply was only 200 m long.

ongoing enhancements

The number and variety of instruments plugged into the array that stream data back to the Internet increases every year. Many of the APL-UW engineers who worked to develop and install the OOI-CA secondary infrastructure, platforms, and instruments are providing critical support to scientists who wish to develop new or modify existing technologies to integrate with the array.

Principal Engineer Dana Manalang, collaborating with University of Washington Professor William Wilcock, devised a simple and elegant modification to ocean bottom pressure sensors so they can return precise measurements at depth for years at a time. During the final leg of the VISIONS'19 expedition, this new ocean bottom pressure sensor was deployed to measure the small and slow vertical movements of the seafloor — deformation — on the Cascadia subduction zone. The sensor gauges the water's weight above it to calculate a measurement of the water's height above the bottom to millimeter precision. Over the span of a year, however, (and the OOI-CA has a design lifetime of 25 years) the measurement accuracy can drift by centimeters, which is many times the value they need to measure. Their solution to the calibration problem is mechanical: a valve placed inside the instrument's titanium housing is activated periodically so that the sensitive quartz crystal is switched from measuring the weight of the ocean to measuring the pressure inside the housing — sealed at 1 atmosphere — as its self-calibrating reference.

A long time series of precise seafloor deformation measurements will provide a new understanding of fault dynamics for marine geophysicists like Wilcock. Where and when is the fault slipping or locked and building pressure? The self-calibrating ocean bottom pressure instrument is just one example of how scientific inquiry and expert engineering, supported by the enabling infrastructure of the OOI-CA, innovate new technologies and create transformational observing capabilities.

apl-uw team members: PAUL AGUILAR, ABLE BACA, ERIC BOGET, BEN BRAND, CHRIS CRAIG, GEOFF CRAM, SKIP DENNY, GRANT DUNN, MIKE HARDING, MIKE HARRINGTON, MIKE KENNEY, TRINA LITCHENDORF, DANA MANALANG, TIM MCGINNIS, CHUCK MCGUIRE, ERIC MCRAE, NICK MICHEL-HART, LARRY NIELSON, JUSTONI ORCEJOLA, KELLEN ROSBURG, ERIC STRENGE, BEAU THOMASON, JAMES TILLEY, KEVIN ZACK

sponsor: NATIONAL SCIENCE FOUNDATION







••• a new era of glaciology and polar oceanography

Jamie Morison, Ben Smith, and Suzanne Dickinson from the APL-UW Polar Science Center, joined by family members and hundreds of other onlookers, waited with anticipation in the pre-dawn hours of 15 September 2018 at Vandenberg Air Force Base in California. All were gathered to watch the moment of blastoff, when the sky was lit in all directions by a Delta II rocket carrying NASA's ICESat-2 into orbit. The launch marked a transition from the years Morison and Smith had spent working on the mission's science definition team to a new phase of observations and discovery. Morison recalls, "At the launch we saw all these people who had similar intense interest and excitement about the project, and we realized how wonderful it is that so much energy, thought, and creativity has been poured into a project so humane — to understand how our Earth is changing."

ICESat-2 is the Ice, Cloud, and Land Elevation Satellite, second generation, that advances the science and technology from the ICESat mission, which spanned 2003–2010. The sole instrument aboard ICESat-2 is the Advanced Topographic Laser Altimeter System — ATLAS. It beams ten thousand pulses of light every second to the Earth's surface, then times every photon's return to the satellite to within a billionth of a second. This yields precise measurements of elevation spanning the Earth's surface from pole to pole, including land ice, sea ice, the atmosphere, vegetation, land, oceans, lakes, and rivers.

For oceanographers like Morison, that means accurate sea surface height retrievals that reveal large-scale currents and circulation, coastal ocean features, and the thickness of polar sea ice. Smith and other glaciologists can use ICESat-2 retrievals of ice surface elevation to study ice sheet seasonal thinning and thickening, outlet glacier rates of change, and dynamic features including lake formation on ice sheets and tidal influences on ice shelves.

Smith used the rich trove of early ICESat data for his doctoral dissertation research, so since the early 2000s he has been aware of their value and limitations to study the great ice sheets of Greenland and Antarctica. Lessons learned and the glaciology community's scientific findings based on ICESat factored heavily into the design and development of the ICESat-2 ATLAS instrument and mission parameters. ICESat carried a single beam profiling altimeter and worked on a 30-day duty cycle; the current mission betters that with three pairs of beams and continuous operation, which should result in nine times better coverage.

Smith's role on the team was to define instrument design and then work out how to turn raw measurements into those that would be useful for glaciologists. That meant translating the most basic measurement made by ICESat-2 — the location from which a particular photon returned — and then gathering enough of those together to say how high the ice was at that time. "The big payoff will be maps of how the ice sheets change over time," notes Smith.

On the ice sheets of Greenland and Antarctica, ICESat-2 resolution and continuous coverage will chart seasonal changes in the ice sheet's surface height, that is, between the end of winter at the time of maximum snow accumulation and the end of the summer melt. Every year that ICESat-2 is in orbit, glaciologists will be able to calculate more precisely the mass flux of the ice sheets.

photo: NASA/Kim Shiflett

In Greenland, the remote and steep terrain has hindered accurate measurements by satellite or any other method. The ICESat-2 beam pair configuration is designed to capture, for the first time, cross-slope tracks at high enough resolution to map elevation changes on slopes of 45 degrees or more. Even dynamic features deep below the ice will be revealed by ICESat-2 measurements of the surface — the subtle inflation and deflation caused by the buildup and outflow of meltwater at the base of ice sheets and the rise and fall of floating ice shelves on the tide. Smith adds, "We'll be able to chart the farthest extent of tidal water getting underneath ice shelves and to measure the grounding lines in ways we haven't been able to so far."

Jamie Morison joined the science definition team to take advantage of the satellite's capability to measure sea surface heights. He notes that there have been many radar altimeter missions to map the open ocean, but few at high latitudes. One motivation to map average sea level is the concern about sea level rise associated with global warming — about 3 mm/year. As an oceanographer, Morison is also interested in the precise measurements of sea surface height that provide maps of pressure gradients — the drivers of upper ocean currents and circulation.

Over ice-covered seas ICESat-2 was designed to detect leads — the thin areas of open water between ice floes. Taking the difference between the height at the top of the ice and the open water yields the average freeboard (the portion floating above the water surface) of sea ice. Freeboard, with some assumptions about snow cover, can be multiplied by about 10 to give the total sea ice thickness. The eventual maps of sea ice thickness, combined with data from other satellites that map sea ice extent, will provide the terms needed to estimate average sea ice volume. "This is really important," stresses Morison, "because our measurements and numerical modeling efforts suggest that over the last 20 years the decreases in extent and thickness have reduced the average sea ice volume in the Arctic Ocean by half."

One year into the mission, ICESat-2 performance is exceeding expectations. Morison reports the success of a calibration and validation experiment. A buoy near Point Barrow, which records GPS measurements of sea surface height using precise point positioning technologies, has been overflown by ICESat-2. Buoy and satellite sea surface height agreed within 2 cm.

At a science team meeting held at APL-UW this past October, investigators reported on the astounding data quality. Current data analyses are revealing the seasonal evolution of fresh water volume in melt ponds and snow depth on sea ice in the Arctic. The instrument has proven its ability to measure the small leads in ice floes, the clouds and blowing snow over Antarctic terrain, and surface wave heights on the open ocean. A team of glaciologists reported the successful charting of tens of millions of ICESat and ICESat-2 orbital crossover locations, yielding estimates of decadal elevation change rates on ice sheets.

apl-uw team members: SUZANNE DICKINSON, JAMES MORISON, BENJAMIN SMITH, TYLER SUTTERLY

sponsor: NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

"We've always had to make bargains with the data we have. Now with ICESat-2, many measurements that had been in soft focus will be very sharp."

– Ben Smith

"I'm excited to see from the preliminary data that we have great resolution. For satellite altimetry it is unprecedented."

– Jamie Morison

sustained focus on the emerging arctic ocean

An international team of researchers boarded the R/V *Sikuliaq* in Nome, Alaska, in September 2018 for a month-long expedition that would take them through Bering Strait to survey the Chukchi and Beaufort seas — one component of the Office of Naval Research's current five-year SODA initiative to understand the rapidly changing ocean-ice-atmosphere system of the Arctic. The dominant oceanographic feature of this region is the flow of relatively warm and salty Pacific Ocean water from the shallow Bering Sea through Bering Strait and into the much colder and increasingly deeper waters of the Chukchi and Beaufort basins.

In September 2018 the feature was particularly dramatic — at one point researchers tracked a 100-m thick wall of 7°C water with current speeds up to 1 m/s pouring into the Beaufort. Informed by satellite-based forecasts beamed to the vessel every day, the research team followed the freight train of ocean heat, poking holes into and slicing through it with shipboard instruments, while casting off and then retrieving drifting platforms to observe the feature as it evolved.

Summer sea ice melt in the western Arctic creates a layer of light, fresh water at the surface. With the dense, warm Pacific water inflow, highly stratified layers form. Much of our current understanding of upper ocean stratification and circulation in the Arctic relies on past measurements, when extensive, persistent ice covered the deep basins. The ice cover isolates the ocean from the atmosphere and, combined with strong vertical density layers, inhibits mixing. The Chukchi and Beaufort seas now, however, are characterized by younger, thinner ice that is easily fractured and deformed. These broken, mobile floes and the increased fraction of open water during summer couple the ocean to the atmosphere more efficiently. Recent observations also suggest that subsurface heat content in the Arctic Ocean has increased over the past decade. Are the mechanisms and rates by which the deep, warm layers mix upward to melt sea ice changing too?

SODA — stratified ocean dynamics of the arctic

Observed changes in the upper ocean stratification in the Beaufort and Chukchi seas and the increased open water during summer months motivated the Office of Naval Research to explore the impact of surface forcing on the upper ocean in the Arctic, particularly the potential for increased turbulence, mixing, and vertical heat transport. The primary field efforts began in summer 2018 and continued through summer 2019, using sensors drifting with the sea ice and within the water column, piloted autonomous vehicles, bottom-moored systems, and intensive ship-based surveys.

photo: San Nguyen

ONR has launched a succession of overlapping initiatives to observe the dramatic recent changes in the Arctic Ocean, to increase understanding of the basic physics driving the ocean–ice–atmosphere system, and to better predict this environment on a variety of time and space scales. These include the recent Marginal Ice Zone initiative (2012–2016), led by Senior Principal Oceanographer Craig Lee, focused on the evolving boundary between open water and pack ice during the spring-to-summer melt and northward sea ice retreat. And the Sea State initiative (2013–2017), led by Senior Principal Oceanographer Jim Thomson, focused on the fall freeze-up period, measuring how ocean heat exchange with the atmosphere and the evolving surface wave field balance to modulate the southward sea ice advance. SODA (2016–2020), with Lee serving as the science steering committee chair, employs many of the observing platforms and strategies developed during these previous initiatives, and completes their arc by measuring, over an entire annual cycle, the upper ocean circulation and dynamics that create and erode stratification in this region of the Arctic.

To achieve a complete annual cycle of in situ observations, another SODA team aboard the USCGC *Healy* transited farther north to deploy a cluster of ice-based buoys, an array of three moorings, and Seagliders to conduct repeat surveys around the array. The buoys drift with their ice floes, measuring meteorological variables, sea ice properties, and temperature, salinity, and turbulence in the upper ocean. The moorings record current profiles, temperature, salinity, wave heights, and the thickness of drifting sea ice above. Distributed on a south–north line the southernmost mooring observed open water, large waves, and an evolving mixed layer during summer while the northernmost remained covered by 1 m of sea ice for the entire year, providing pictures of both the 'new' and 'old' Arctic. "Through ONR support, we have demonstrated the utility of autonomous observing platforms to capture the vast scales of variability in the Arctic," notes Lee, who served as chief scientist aboard the SODA 2018 and 2019 *Healy* cruises to deploy and recover the instruments. "These technologies provide persistence and mobility, and have relatively lightweight logistical requirements."

Aboard the *Sikuliaq*, led by cruise chief scientist Jennifer MacKinnon from the Scripps Institution of Oceanography, the team pursued an unconventional cruise plan — one that served well during the Sea State initiative. Relying on weather and ice forecasts produced from satellite observations and received by the ship every day, they could identify locations of interest to measure processes as they were unfolding. The strategy was a success in that they had several opportunities to observe subduction, where warm, dense layers slipped underneath cold and fresh, as well as find evidence of small-scale eddy structures that stir dense water both vertically and laterally, perhaps the instigators of subduction and stratification.

While Mackinnon's group targeted a volume of the upper ocean with zig-zagging fast conductivity-temperature-depth surveys to unravel the complicated picture subsurface, Thomson's team deployed surface drifting platforms to capture the evolving atmospheric, wave, and sea ice conditions. "Jennifer was trying to figure out how the upper ocean is mixing and we were helping to tell her how much of that is because of direct connections to the atmosphere," recalls Thomson. Combined, they could estimate a budget of how much inflowing ocean heat was moving laterally into the basin and how much was escaping vertically to the atmosphere. In mid-September, with the sun low on the horizon and cold temperatures, the team estimated that at least one-half of the heat rolling in was lost to the atmosphere before arriving in the Beaufort Sea basin.

The researchers also encountered an anomalous remnant band of sea ice in the southern Beaufort Sea that had persisted through the summer melt season. This presented the opportunity to sample the ocean under and downwind of a protective layer of sea ice. Measurements from SWIFT (Surface Wave Instrument Float with Tracking) drifters deployed around the ice island revealed stark contrasts — different surface mixed layer properties, and larger waves and greater turbulence on the windward than the leeward sides.

These detailed snapshots of small-scale features and motions that evolved rapidly, combined with the annual time series gained from the ice-based and moored instruments will help to complete a picture of how surface forcing and the potential for increased turbulence, mixing, and vertical heat transport affect upper ocean stratification in the emerging Arctic Ocean.

apl-uw team members: ERIC BOGET, SAMUEL BRENNER, LAURA CREWS, ERIK DAHL, JASON GOBAT, JOHN GUTHRIE, BEN JOKINEN, ALEX DE KLERK, CRAIG LEE, JAMES MORISON, LUC RAINVILLE, MADISON SMITH, JOE TALBERT, JIM THOMSON

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academic achievements

We recognize with pride the graduate students who have earned advanced degrees in the past biennium and the APL-UW scientists who served as their research and thesis advisors.

Though the Laboratory itself does not grant degrees, 40 Laboratory scientists hold faculty appointments in University of Washington academic departments, principally in the College of Engineering and College of the Environment, which includes the schools of oceanography and aquatic and fishery sciences.

Every year APL-UW scientists support scores of postdoctoral researchers, and graduate and undergraduate students who are matriculated in UW departments.

Sam Brenner Oceanography, M.S., 2019
The Evolution of a Shallow Front in the Arctic Marginal Ice Zone
Jim Thomson and Luc Rainville

Roxanne Carini Civil and Environmental Engineering, Ph.D., 2019
Geometry, Kinematics, and Energetics of Surf Zone Waves Near the Onset of Breaking Using Remote Sensing
Chris Chickadel and Andrew Jessup

Nan-Hsun Chi Oceanography, Ph.D., 2018
Surface Mixed Layer Heat and Salinity Budget in the Central Equatorial Indian Ocean
Ren-Chieh Lien

Sarah Dewey Oceanography, Ph.D., 2019
Evolving Ice–Ocean Dynamics of the Western Arctic
James Morison

Dara Farrell Mechanical Engineering, Ph.D., 2019
Metrics and Statistical Modeling of Ambient Noise with Emphasis on Calving Noise from a West Greenland Fjord
Peter Dahl

Mohamed A. Ghanem Aeronautics and Astronautics, Ph.D., 2018
Acoustic Manipulation of Macroscopic Objects
Michael Bailey and Adam Maxwell

Maricarmen Guerra Civil and Environmental Engineering, Ph.D., 2018
Flow Characterization for In-Stream Energy Sites
Jim Thomson

Je-Yuan Hsu Oceanography, Ph.D., 2017
Estimates of Drag Coefficients and Surface Waves Under Tropical Cyclones Using Subsurface EM-APEX Floats
Ren-Chieh Lien

Leah Johnson Oceanography, Ph.D., 2018
Stratification at Ocean Fronts
Craig Lee

Paul Kintner Earth and Space Sciences, M.S., 2017
New Estimates of Ice and Oxygen Fluxes Across the Entire Lid of Lake Vostok from Observations of Englacial Radiowave Attenuation
Dale Winebrenner

Kaylie McTiernan Mechanical Engineering, M.S., 2018
A Heuristic Optimization Approach to Hydrodynamic Wave Energy Converter Geometry
Benjamin Maurer

Brett A. Morris Oceanography, M.S., 2019
Seasonality and Forcing Factors of the Alaska Coastal Current in the Bering Strait from July 2011 to July 2012
Rebecca Woodgate

Thomas Powers Electrical Engineering, Ph.D., 2019
Differentiable and Robust Optimization Algorithms
David Krout

Akshay P. Randad Mechanical Engineering, M.S., 2018
Design, Fabrication, and Characterization of Ultrasound Transducers for Fragmenting Large Renal Calculi
Adam Maxwell and Michael Bailey

Madison Smith Civil and Environmental Engineering, Ph.D., 2019
The Role of Waves in the Autumn Arctic Ocean
Jim Thomson

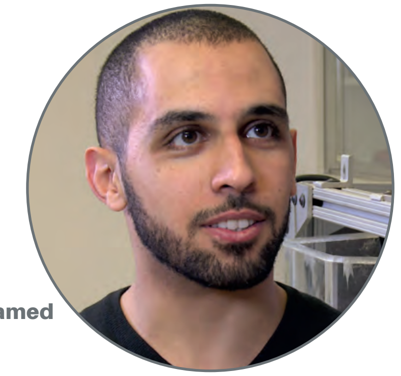
Alex Soloway Mechanical Engineering, Ph.D., 2018
Environmental Noise from Underwater Explosions and the Impact of the Seabed on the Received Levels
Peter Dahl

Yushi Tan Electrical and Computer Engineering, Ph.D., 2019
Power System Resilience Under Natural Disasters
Payman Arabshahi and Daniel Kirschen

Nora Webb Williams Political Science, Ph.D., 2019
Colonial Policy, Social Trust, and Economic Resilience: The Long-Term Impacts of Imperial Russian Settlement in Southern Kazakhstan
Michael Gabbay


Alex


Sarah


Mohamed


Roxanne


Thomas

financial health

We are pleased to report that the Applied Physics Laboratory has experienced steady financial growth over the past biennium. This growth has brought the Laboratory back to the record levels reported in 2015.

The total grant and contract awards received by APL-UW for federal fiscal years 2018 and 2019 was $143.9M, exceeding the total reported in our previous biennium by more than $23M.

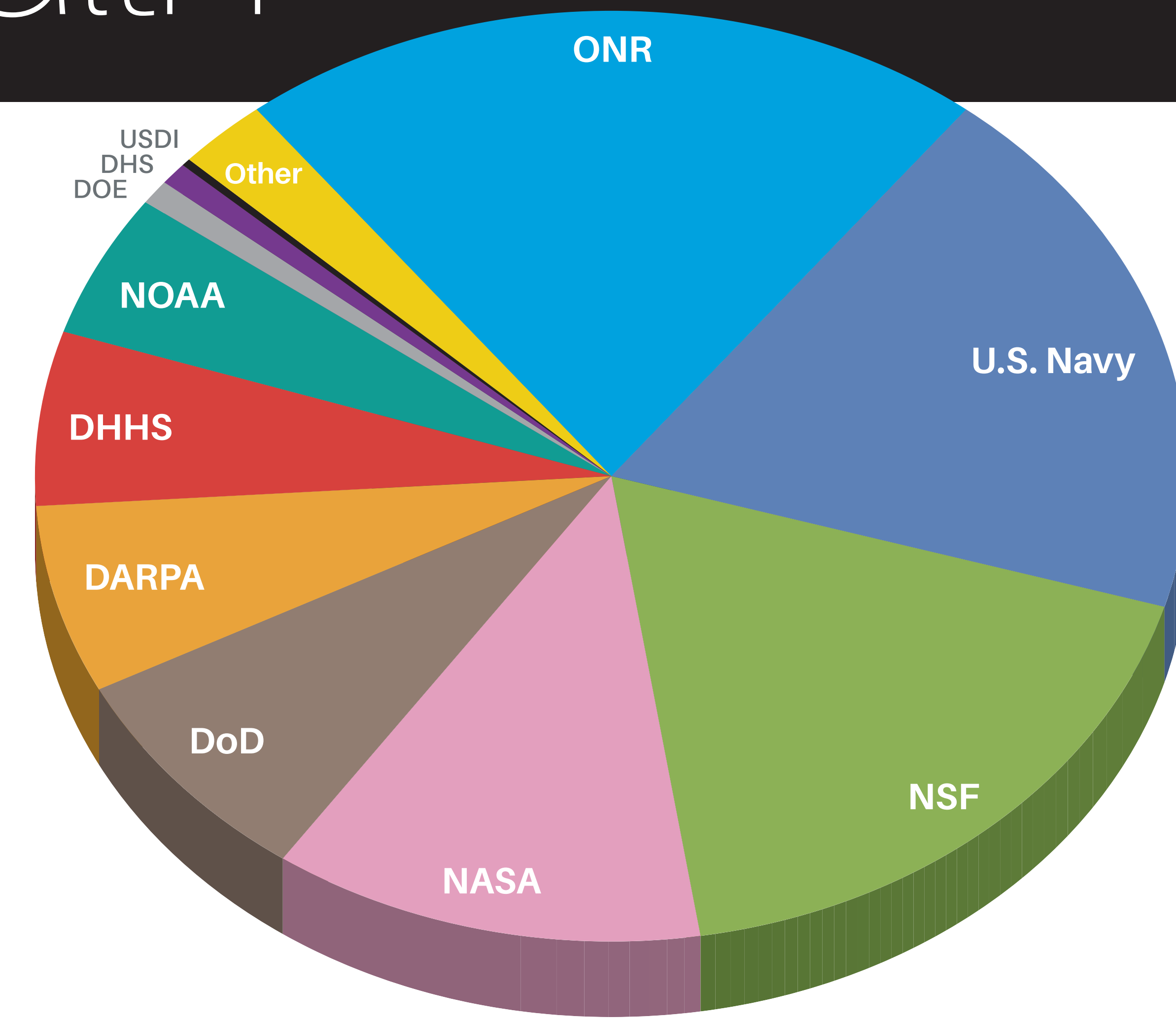
A valuable dividend of increased grant revenues is the growth in prorated direct cost and fee discretionary funds, which allow further investments in our people and enabling infrastructure, ensuring APL-UW will continue to lead in scientific discovery and technology innovation.

The U.S. Navy remains the largest sponsor of Laboratory research and development. Funding from all Navy sources represented 41% of federal awards and 40% of all awards received in 2018–2019. The Office of Naval Research continues to be the greatest source of Navy funds, representing 21% of awards received. The Laboratory, too, has received significant increases in funding from the Naval Surface Warfare Center and the Naval Facilities Engineering Command, with $6M and $8M, respectively, received over the biennium. The Defense Advanced Research Projects Agency and non-Navy Department of Defense agencies remain strong sponsors, representing 7% and 8%, respectively, of all awards received.

Grant awards from the National Science Foundation totaled $25.9M, representing 18% of the funding accounted for 2018–2019. And the National Aeronautics and Space Administration continues to be the second largest non-defense federal sponsor, funding 12% of all awards.

The Applied Physics Laboratory's defining strength is the integration of fundamental scientific expertise and applied technology development under one roof. The balance of funding has shifted between basic and applied research over the years. Over the last biennium, the funding distribution was more evenly balanced than in previous years, with basic research representing 43% of all awards and applied research and development representing 57%. This balance more accurately reflects our continuing acknowledgment that the successful integration of our research and development portfolio furthers leading-edge science and engineering.

The Laboratory is entering an exciting period of change. Over the next biennial period we are engaging in efforts to make significant investments of discretionary resources — investments in new investigators, post-doctoral researchers and fellows in promising new research and development areas, investments to grow the expertise of our professional engineers, and investments in facilities and infrastructure that will ensure the Laboratory's ability to respond quickly to the needs and changing priorities of our research sponsors.



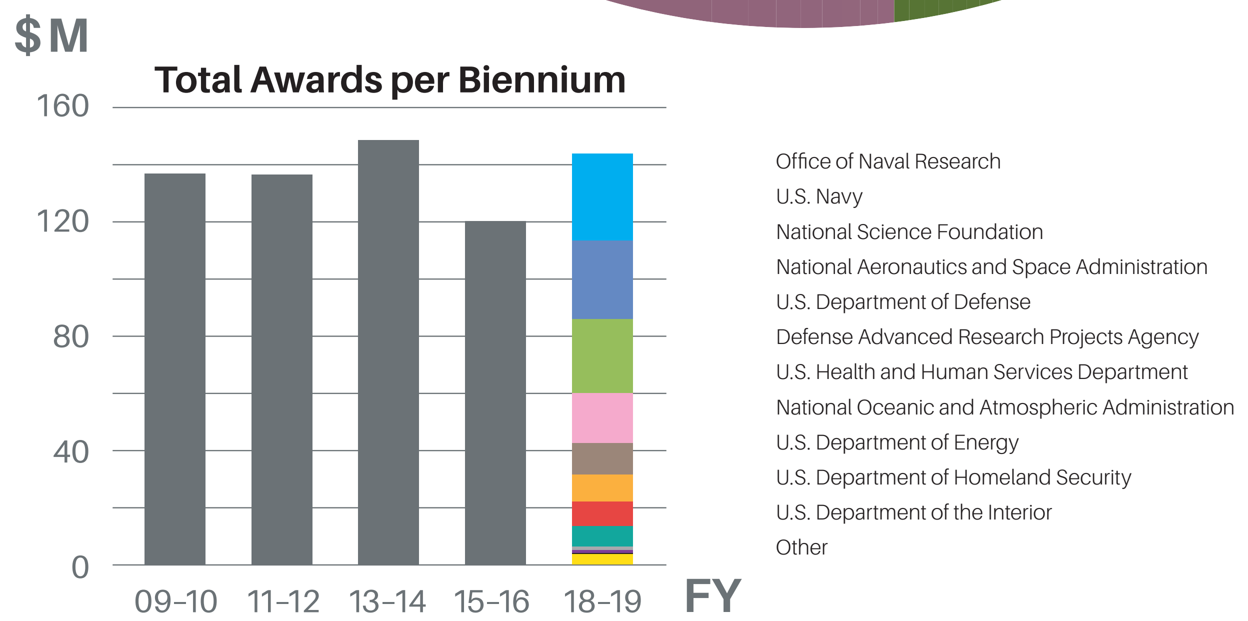


photo: Pacific Marine Energy Center

a blue economy powered by marine renewable energy

Throughout the summer of 2019, a research team conducted tests of a full-scale prototype tidal turbine and the systems that control and measure its performance aboard APL-UW's newest vessel, the R/V *Russell Davis Light*. This cross-flow turbine, developed by engineers at APL-UW and the University's Department of Mechanical Engineering, is efficient and robust, with only one moving part.

Mounted in a purpose-built gantry, the turbine is lowered between the catamaran hulls. With the vessel underway to simulate tidal flows, tests of rotor design, powertrains, generator performance, and electronic controls are repeated under various controlled conditions.

The team was honored by a visit from Washington State Governor Jay Inslee, who launched early this year the Maritime Blue Initiative to bolster innovation, create jobs, protect the environment, and ensure sustainability in the regional maritime industry.

During tidal turbine tests Governor Inslee learned more about our partnership with the Pacific Marine Energy Center — a consortium of researchers from the UW, Oregon State University, and the University of Alaska Fairbanks working to advance reliable, renewable marine energy through scientific research, stakeholder engagement, and education.

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