APL-UW

december 2017

biennial report

APPLIED PHYSICS LABORATORY
UNIVERSITY OF WASHINGTON

Preparing the Surface Salinity Profiler for deployment during a research expedition in the eastern tropical Pacific Ocean

photo: Andy Jessup

what we do...

advance scientific discovery + invention

enhance national security

educate future generations of scientists + engineers

Established in 1943 at the request of the U.S. Navy, the Applied Physics Laboratory of the University of Washington has provided continuous access to the highest levels of academic expertise in scientific research and engineering to address Navy-specific problems.

Based on our broad and deep experience in undersea science and technology, APL-UW is one of only five University Affiliated Research Centers (UARCs) designated by the Department of Defense that have long-term, large-scale, formal connections to the U.S. Navy.

Laboratory expertise spans acoustic and remote sensing, ocean physics and engineering, medical and industrial ultrasound, polar science and logistics, environmental and information systems, and electronic and photonic systems.

APL-UW is making a world of difference through innovative science, engineering, and advanced education.

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discovery, invention, service

This APL-UW *Biennial Report* contains a sampling of the exciting scientific discoveries, technological developments, educational highlights, and outreach endeavors of the Applied Physics Laboratory of the University of Washington over the past biennium. The Laboratory continues to expand its research and development portfolio, and here we report on some new areas of expertise — the coupling of physical and biological systems in the marine environment, robotics and autonomy, and marine hydrokinetic energy — as well as our traditional areas such as ocean physics and acoustics in the human body and under water. The report also highlights recent field experiments, outreach efforts, and research performed by talented young investigators at APL-UW.

This is the eighth *Biennial Report* cycle of my tenure as the APL-UW Executive Director, and it will be the last one for me. It has been a privilege to serve, now nearly 15 years, as the head of this exemplary institution, but it is time for me to move on. The APL-UW team has accomplished much together — expanding the breadth and funding of research and development programs, improving our enabling infrastructure, recruiting and integrating research and administrative staff, and enhancing overall productivity.

Responding to regional and global needs, APL-UW established major research and development initiatives across a breadth of areas during the past 15 years. To name a few areas: ocean observing systems, operational ocean gliders, counter-IED measures, ultrasound for molecular imaging and therapy, marine hydrokinetic energy, Puget Sound monitoring, mid-frequency acoustic reverberation, remote sensing of river and maritime environments, oceanography of the western Pacific, and the changing Arctic. Some of these major initiatives, as well as other smaller research programs, for example, in cybersecurity, opened completely new R+D domains for us. During the same period, federal research funding increased markedly for APL-UW; our portfolio of key sponsoring agencies has diversified, and APL-UW negotiated its largest and longest contract ever with the U.S. Navy (NAVSEA).

During these years, APL-UW also expanded into two new buildings, adding quality laboratory and office space. This enlarged footprint enabled decompression, boosted recruitment, and provided laboratories with unique and advanced capabilities. We also acquired a superior storage and staging facility and a new and more capable vessel for Puget Sound and Pacific coastal research. Launching the twice-weekly "Business Exchange" has encouraged collegial interactions and fostered new collaborations within and external to the Laboratory. Synchronized with the UW, we began to modernize our business and finance processes and integrate them more closely with campus financial systems.

"The talented people of APL-UW have labored tirelessly to develop our Laboratory into an efficient and outstanding resource for discovery, invention, application, and education."

I am proud to report that during my tenure we have recruited exceptional researchers and increased our number of scientists and engineers, more than doubling the number of women in this group. Mutually beneficial collaborations between Laboratory and University researchers strengthened, especially in the areas of ocean and ice environments, engineering and medicine, and meaningful academic appointments shared between APL-UW and University departments were added. We found ways to improve connectivity with industry, including teaming with commercial partners in a common workspace — The Collaboratory at APL-UW. We also reorganized the Laboratory's management structure, refreshed our Advisory Board, and, most importantly, moved to a new higher, and more central, report within the UW.

In the last 15 years, APL-UW researchers have increased their productivity dramatically, as measured by technology and knowledge transfer. The number of patents and licenses of intellectual property rose considerably, and the rate of Laboratory spinoff companies grew 10-fold. Knowledge transfer benefited from the increase in the number and quality of scientific publications and the frequency of fieldwork and the valuable datasets collected. Knowledge transfer to the public improved as well, through strategic outreach that resulted in the regular production of video features and an increase in media coverage of Laboratory research. For their innovation, many APL-UW scholars garnered prestigious national and international awards and recognition, and Laboratory productivity contributed to the UW's prominent position in rankings of world universities.

Transitions of APL-UW technology directly to the U.S. Navy fleet remain robust. Since the Laboratory's beginning, most of these transitions have been, and continue to be, software and hardware developments or other contributions that serve to maintain U.S. undersea superiority. I had the pleasure recently to witness the commissioning of the newest nuclear submarine, USS *Washington*. It is the first Navy vessel in more than seven decades to be named after the state of Washington, and it is fitting that it enters the fleet near the same time our Washington-based Laboratory, so dedicated to undersea superiority, begins celebrating its 75th anniversary.

I have had the great honor to work with an extraordinary staff at APL-UW. I am extremely thankful to this team, comprised of all my APL-UW colleagues, past and present, for their commitment and hard work, and for the trust they placed in me. I also want to express my gratitude to our home institution, the University of Washington, and our federal sponsors — especially the U.S. Navy and Department of Defense, National Science Foundation, National Aeronautics and Space Administration, National Oceanic and Atmospheric Administration, and National Institutes of Health — for their generous and steadfast support over the past years. I will miss steering the APL-UW ship, and I wish you all fair winds and following seas.

Jeff Simmen

photo: Tim McGinnis

research + development

harvesting power from the sea

Marine energy is persistent and predictable. Harvesting this ubiquitous yet untapped resource will provide strategic, tactical, and operational advantage to the U.S. Navy.

ultrasonic therapies: fast, painless + effective

Patients suffering from two common afflictions — abscesses and hematomas — may someday find relief with ultrasound therapies that liquefy targeted tissue inside the body with no damage to the intervening tissue.

photo: Kate Stafford

a rapidly changing climate for arctic marine mammals

An ice-diminished Arctic Ocean has wide-ranging implications for animals such as polar bears and beluga whales, whose movements are coordinated with annual sea ice cycles.

photo: Lucas Boland, UW

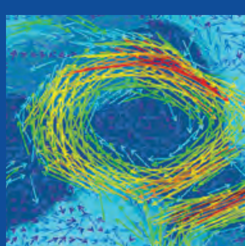
ocean observations by swarm

Swarms of ocean robots that float, sink, and rise in unison measure oceanographic properties. In the North Pacific they captured the evolving three-dimensional structure of de/re-stratification events in response to storms.

photo: Robert Snow, OCEARCH

abundant ecosystems lurk deep in ocean eddies

A study of ecosystem variability in the North Atlantic is informed by data from an unlikely oceanographic research platform: white sharks.



idea to impact — software engineering is key

Innovative programmers enhance handheld devices so researchers can collect data after natural disasters, write code so pilots can control fleets of robots in distant oceans, and create onboard intelligence for undersea vehicles to navigate autonomously.

harvesting power from the sea

Marine energy is persistent and predictable. The U.S. Navy's long-range energy strategy has two top priorities: security and independence.

Harvesting this ubiquitous yet untapped resource will provide strategic, tactical, and operational advantage.

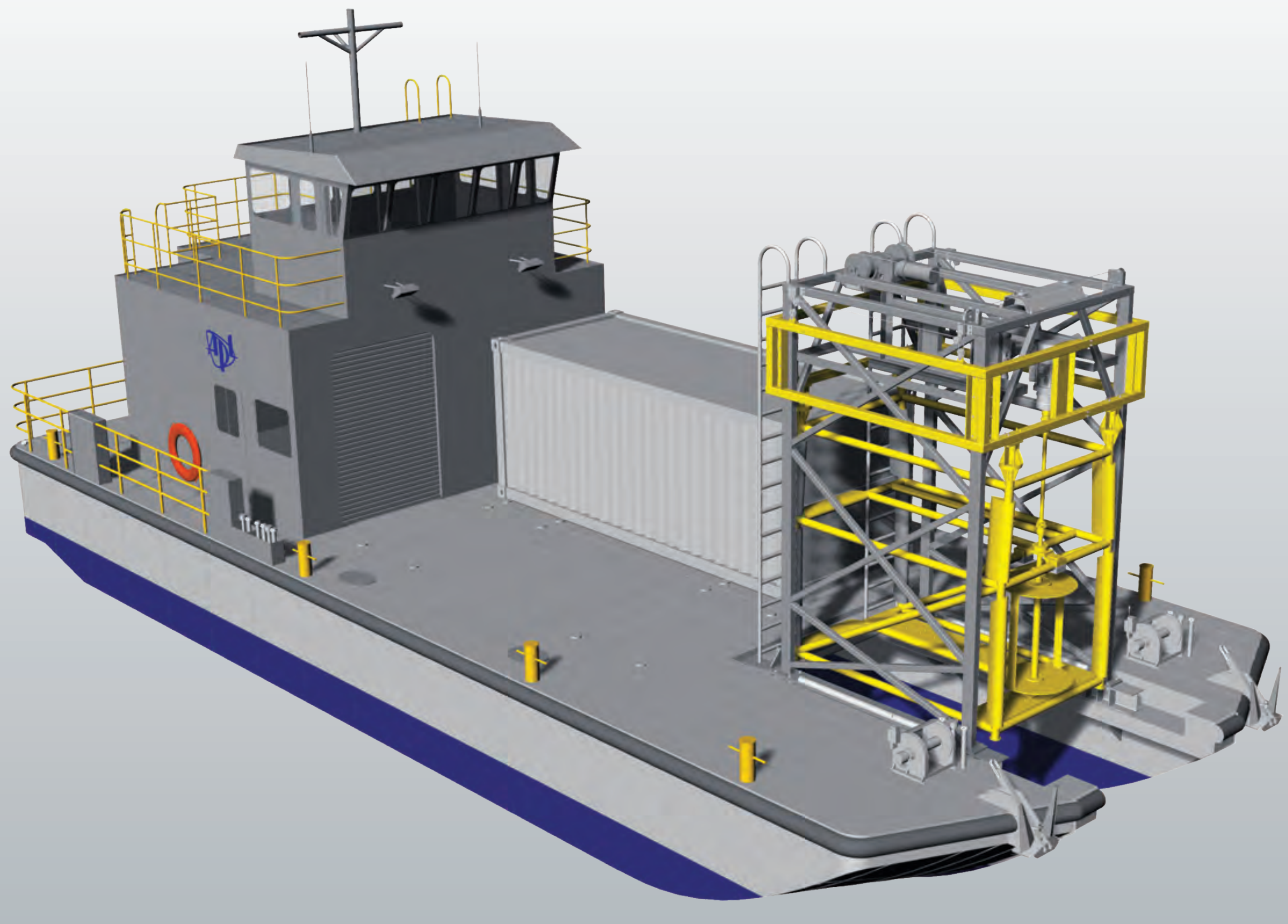


image: Aurora Marine Design

Scientists, engineers, and students are investigating all aspects of marine energy technologies. “Our efforts at APL-UW rely on academic and industry collaborators,” explains Principal Engineer **ANDY STEWART**. “Our goals are to advance marine energy technologies and enable adoption of generation capabilities at naval installations, where they will provide cost-effective, predictable, and reliable on-site power at multiple scales.”

fundamental physics >> applied engineering

Marine energy technologies convert the movement of waves, tides, and currents into usable power. Devices can heave, pitch, and roll to capture wave energy. Turbines, positioned across a flow, spin custom power takeoff units to drive generators.

A key component of marine energy technology advancement is to investigate cross-flow turbines from lab-scale research and development to full-scale prototype testing and evaluation in the field. Collaborators in the UW Department of Mechanical Engineering ran fundamental design and performance experiments for hundreds of hours with lab-scale turbines in the flume at the UW’s Harris Hydraulics Laboratory. What hydrodynamic surfaces are most efficient? In variable flows, how are optimal turbine rotation speed and torque maintained? Can an array of turbines produce more power than those spinning individually?

The engineers discovered they could increase turbine power output by controlling the turbine’s speed within each rotation. That is, maximizing the time when the rotors are harvesting the flow at peak efficiency increases the power generated by over 50%. “Our mechanical engineering collaborators also found that cross-flow turbine rotors shed vortices into their wake,” reports Senior Engineer **BEN MAURER**. “It turns out that two turbines can work together. Precise positioning and timing of their rotation coordinates the downstream turbine’s interaction with the vortices and increases the total power.”

The laboratory model experiments produced an efficient, structurally robust turbine with only one moving part. Now APL-UW investigators will engineer, test, and evaluate prototypes capable of producing kilowatts of power. Field-scale turbines will be tested aboard a new purpose-built vessel that can be driven to generate currents in a lake, or moored in a tidal current. With turbines lowered and raised in and out of the current by the vessel’s gantry system, tests of rotor design, powertrains, generator performance, and electronic controls can be repeated and varied under controlled conditions.

To investigate power generation at naval installations, prototype turbines will be deployed on the seafloor at the Pacific Northwest National Laboratory facility at Sequim Bay. "These long-term test bed deployments are invaluable, and will provide new insights into how best to advance these technologies for the U.S. Navy," anticipates Maurer.

How do real-world conditions, such as turbulence, debris, the changing direction and strength of tidal currents, biofouling, and storm surges affect turbine power performance and reliability? "During the deployments at PNNL, we'll be working on a system to collect and smooth the inherently variable power from multiple turbines," explains Senior Engineer **ROB CAVAGNARO**. "The system will electrically couple turbines so the combined power is more consistent than if they were operating separately."

monitoring environmental effects

As turbines spin in strong currents, is marine life at risk? What about the noise? Does it affect animals' behavior, especially the marine mammals that rely on underwater sound to navigate, communicate, and forage? The Adaptable Monitoring Package keeps eyes and ears on the environmental effects of marine energy conversion by putting the right mix of sensors near converters to capture the biology–technology interactions.

Nearly any sensor that communicates over an Ethernet or serial connection and runs on electrical power can be plugged into the AMP. It can be configured with hydrophones, an acoustic camera, a multibeam sonar, stereo optical cameras to collect photos and videos, as well as an acoustic Doppler current profiler to measure water velocity. "Integrating multiple instruments is fundamental to AMP's success," explains Senior Engineer **JAMES JOSLIN**. "Having instruments with varying range and bandwidth allows the AMP to provide high-resolution data over a larger area of interest."

Sounds and images of fish, seals, and diving seabirds have been collected. These varied marine life encounters with energy converters are infrequent, so data must be processed continuously and saved only at the moment of interaction. With software control, the AMP's sensors can detect marine animals and trigger data capture. For example, the acoustic camera may detect a seal swimming past and will trigger the stereo optical cameras to capture images. Student researchers are now using machine learning algorithms with training data sets collected by the AMP. Their enhanced software controls will make the tasks of target detection, triggering, and animal classification automatic.

Ever adaptable, the AMP can be deployed as a standalone tripod lander or integrated with underwater structures by mating the sensor package with a small remotely operated vehicle. The ROV flies the sensor package to a docking station on the structure, separates, and flies back to the surface for recovery. A fiber-optic cable connects the AMP to its onshore power supply and computer control. An autonomous version has been deployed; it is battery powered and has all its control and data acquisition software on board. In early 2018, as part of a micro-grid demonstration at the Navy's wave energy test site in Hawaii, an AMP will be mated to a wave energy converter where the WEC itself powers the environmental monitoring sensors, control software, and data storage devices.

research + education

The success of these research collaborations is due, in large part, to the Northwest National Marine Renewable Energy Center, a partnership among the UW, Oregon State University, and the University of Alaska Fairbanks, that coordinates research efforts. Broadly, the center's goals are to conduct research that facilitates commercialization of marine energy technologies and informs regulatory and policy discussions. **BRIAN POLAGYE**, NNMREC Director and Associate Professor of Mechanical Engineering at the UW, highlights the center's accomplishments. "Established in 2008, the center has made significant contributions that reduce the cost of energy for a range of marine energy converters, has developed the technologies and methods to forecast and characterize the resources at potential marine energy sites, and has been a global leader in understanding environmental and socioeconomic effects."

A hallmark of a major research university is that scientific inquiry and student development go hand-in-hand. "The caliber of students attracted to the field of marine energy by NNMREC is impressive," notes Stewart. "Many of them have gone on to make waves in the industry and some have become integral members of our research group since finishing their degrees." At APL-UW students have been entrained in the funded marine energy research projects since the first award was received. They are the future innovators and workforce for the sector.

apl-uw marine energy team: **ERIC BOGET, ADAM BROWN, JUSTIN BURNETT, ROBERT CAVAGNARO, ALEXANDER DE KLERK, JESSE DOSHER, MICHAEL EINHORN, PAUL GIBBS, LARRY JOIREMAN, JAMES JOSLIN, AARON MARBURG, BENJAMIN MAURER, TIMOTHY MCGINNIS, NICHOLAS MICHEL-HART, BRIAN POLAGYE, CHRIS SIANI, ANDREW STEWART,** and **JIM THOMSON**

sponsors: **NAVAL FACILITIES ENGINEERING COMMAND, DEPARTMENT OF ENERGY, DEFENSE ADVANCED RESEARCH PROJECTS AGENCY, OFFICE OF NAVAL RESEARCH,** and **WASHINGTON STATE DEPARTMENT OF COMMERCE**

webs

An offshore, free-drifting power station was built and tested successfully in the open ocean by APL-UW engineers last year. WEBS, the Wave Energy Buoy that Self-deploys, converts surface wave energy to mechanical and electrical power.

“As opposed to typical wave energy devices that are anchored to the seafloor and cabled to shore to provide sustained power needs, WEBS is all about having an easily deployed power station anywhere offshore,” explains Principal Engineer Andy Stewart.

WEBS drifts on the ocean surface. Passing waves force its surface expression to rotate relative to a central driveshaft. This rotary motion is passed through a gearbox and generators to produce electricity. A heave plate tethered 60 m below remains stationary in the water column, providing something for the surface unit to pull against.

Potentially, it could power sensor payloads on scientific instruments, autonomous systems, undersea vehicles, and surface vessels, as well as serve as a communications relay.

photo: Andy Stewart

ultrasonic therapies: fast, painless + effective

Patients suffering from two common afflictions that have poor treatment options may someday find relief with 'game-changing' ultrasound therapies. Researchers at the Center for Industrial and Medical Ultrasound and their collaborators are exploring the treatment of deep abscesses and large hematomas noninvasively and painlessly with focused ultrasound.

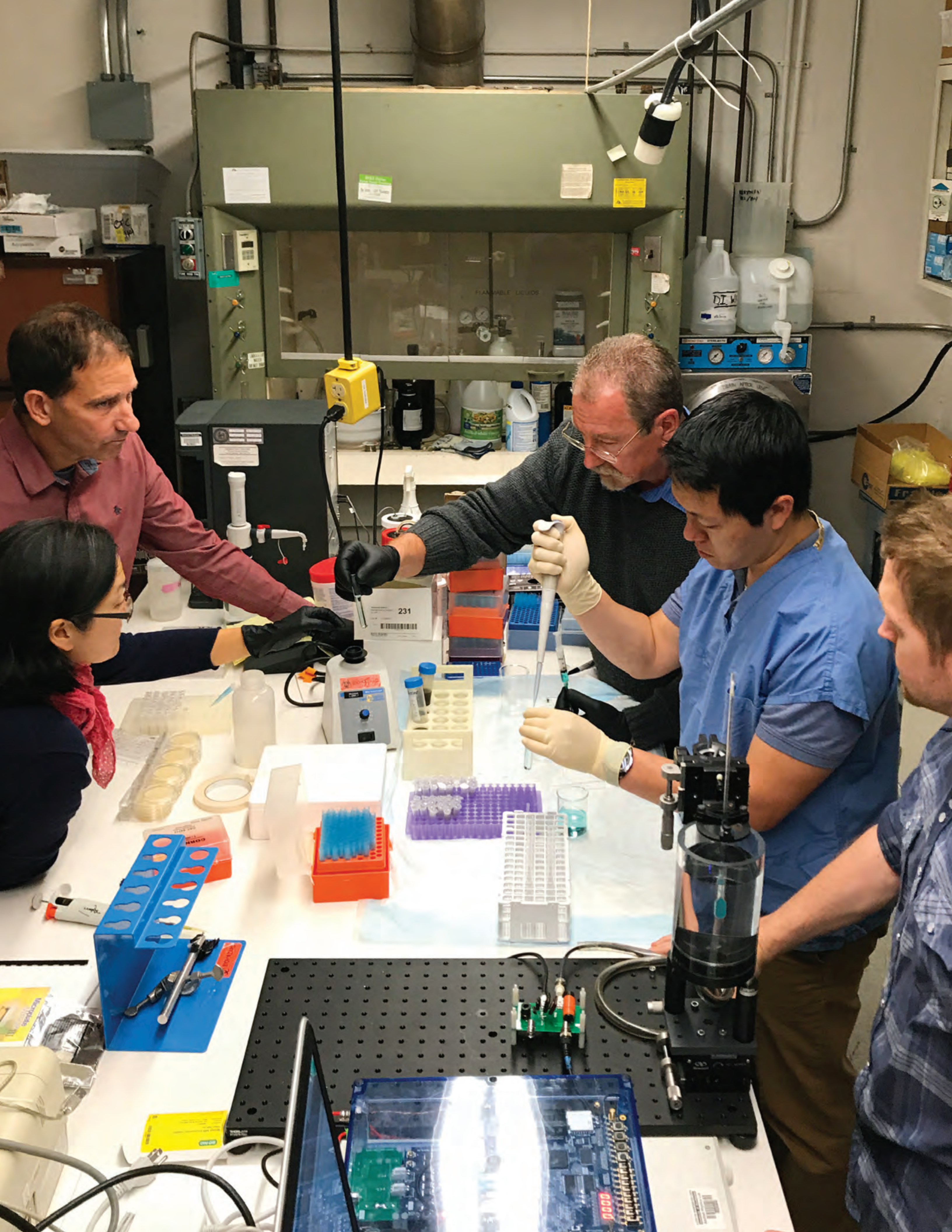
Abscesses — fluid-filled cavities in the body harboring bacteria — are treated by interventional radiologist Dr. **KEITH CHAN** at Tacoma (WA) Radiology Associates. Chan explains, "Patients come into the hospital after appendicitis or a surgical procedure. They don't feel well. Using an imaging technique, CT or ultrasound, we see that they have an abscess and we start them on antibiotics. Then treatment is as it has been for the past 2000 years — when there is a build-up of bacteria in the body, you have to get rid of it by draining it."

Hematomas — the leaking or discharge of blood from a damaged vessel to the surrounding tissue — result from blunt force trauma and can occur in professional athletes who sustain muscle injuries from repetitive stress. Though the pain can be debilitating, treatment options are limited. And unlike abscesses, drainage is often impossible; hematomas are gelatinous and will not flow easily through a catheter.

Laboratory experiments with bacteria in fluid suspension and real human pus drained from abscesses show that a short ultrasound treatment kills virtually all the bacteria. Benchtop experiments with a large hematoma phantom show that focused ultrasound treatment emulsifies the hematoma in only a few minutes, indicating that ultrasound may be a rapid, definitive intervention to relieve the pressure on adjacent tissues or organs.

> **"These collaborative teams are tackling some hard questions in therapeutic ultrasound. And sometimes we find applications that have the potential to upend current treatment paradigms, providing patients with better care at lower costs."**
>
> – Tom Matula

Currently, a patient presenting with a deep body abscess faces a two-hour surgery, where the doctor pierces the abscess and inserts the drain, which must be sutured in place. Then for several days to weeks, the patient must live with the catheter and collection bag. Clogged drains, secondary infections at the drainage site, and the risk of jarring the drain loose are common complications that require expensive re-hospitalization. Those with hematoma injuries face a typical recovery time of 10 to 30 weeks following the standard RICE protocol of rest, ice, compression, and elevation.



Dr. Chan uses ultrasound imaging routinely in his clinic, and during a meeting with CIMU Director **TOM MATULA** they came upon the ultrasound solution for Chan's daily challenges with abscesses. What if the same ultrasound probe used for an imaging diagnosis could also deliver the therapeutic dose to treat the abscess by killing the bacteria? In a similar brainstorming session, Matula, his colleagues **YAK-NAM WANG** and **TANYA KHOKHLOVA**, and interventional radiologist Dr. **WAYNE MONSKY** of the UW Medical Center, came upon the potential of focused ultrasound to emulsify hematomas.

Like focusing the sun's rays through a magnifying glass, focused acoustic waves produce thermal effects, but they also produce important mechanical effects. Treatment of hematomas and abscesses relies on the ability of ultrasound to disintegrate cells by tearing them apart mechanically. To heighten this mechanism and suppress heating, CIMU engineers **BRIAN MACCONAGHY** and **ADAM MAXWELL** designed and built transducers and amplifiers that generate specific acoustic pressures and pulse parameters.

When a sequence of millisecond-long focused ultrasound pulses is delivered by the transducer, the profile of the initially harmonic wave steepens, becomes nonlinear, and a high-amplitude shock forms at the acoustic focus. CIMU investigators discovered that these shock fronts create instantaneous heating that, in turn, generates millimeter-sized boiling bubbles at the focal region. Each subsequent acoustic pulse and resulting shock front interacts with the bubbles' vapor cavity, which generates extreme shear forces that rip apart any cellular material near the focus.

"We're really hoping that in ten years this is the accepted standard for abscess treatment."

Mechanical disintegration of hematomas produces lesions of liquefied tissue. Because the acoustic focusing is very precise, lesions have clearly defined margins and adjacent tissue is spared mechanical and thermal damage. The liquefied tissue may be more easily resorbed by the body or, as demonstrated in lab experiments with a hematoma phantom, removed by fine-needle aspiration. Targeting an abscess for ultrasound treatment means finding the center of the collection space. "You can focus in one spot and the streaming fluid brings the material into the acoustic focus, so the effective treatment volume is much larger than the focal region," remarks Matula.

Keith Chan is optimistic about ultrasonic therapies. "We're really hoping that in 10 years this is the accepted standard for abscess treatment. We will look back at open surgery or catheter drainage and know we've come a long way."

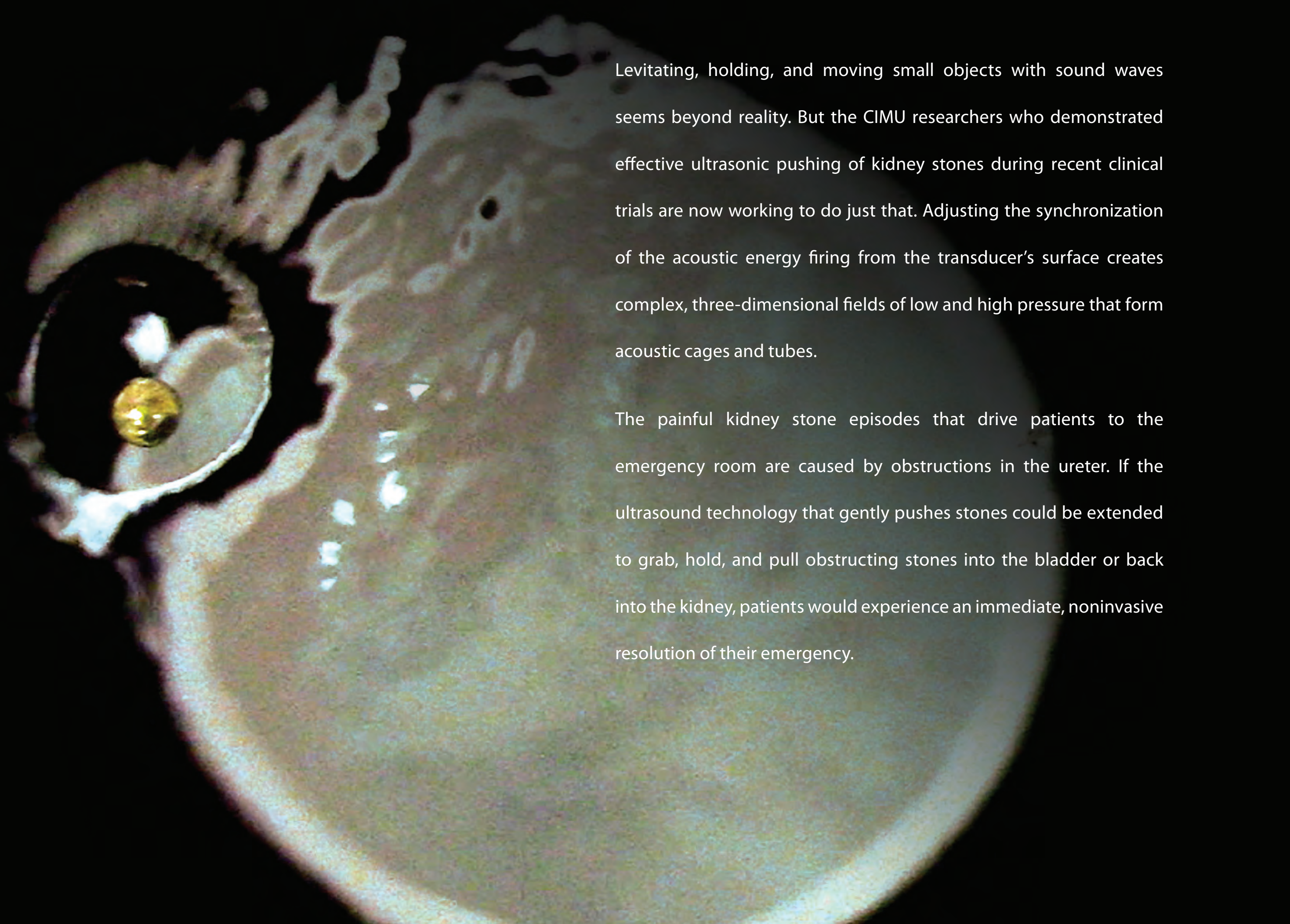
ultrasonic abscess team: **ANDREW BRAYMAN, KEITH CHAN, BRIAN MACCONAGHY, THOMAS MATULA,** and **YAK-NAM WANG**

ultrasonic hematoma team: **TANYA KHOKHLOVA, BRIAN MACCONAGHY, THOMAS MATULA, WAYNE MONSKY,** and **YAK-NAM WANG**

innovation imperative: toward clinical therapies

CIMU investigators received a U.S. patent last year for the devices and methods used to study hematoma treatments with ultrasound. The technique to emulsify tissue through ultrasonic atomization holds promise for many clinical applications that require tissue ablation. Physician researchers at the UW School of Medicine are collaborating with the CIMU science and engineering team. Besides large hematoma therapy, they are investigating the treatment of pancreatic and kidney cancers. Mechanical ablation of tumors with focused ultrasound replicates the benefits of surgical removal, but without the damage to healthy tissue and associated recovery.

tractor beams are science fact, not fiction



Levitating, holding, and moving small objects with sound waves seems beyond reality. But the CIMU researchers who demonstrated effective ultrasonic pushing of kidney stones during recent clinical trials are now working to do just that. Adjusting the synchronization of the acoustic energy firing from the transducer's surface creates complex, three-dimensional fields of low and high pressure that form acoustic cages and tubes.

The painful kidney stone episodes that drive patients to the emergency room are caused by obstructions in the ureter. If the ultrasound technology that gently pushes stones could be extended to grab, hold, and pull obstructing stones into the bladder or back into the kidney, patients would experience an immediate, noninvasive resolution of their emergency.

a rapidly changing climate for arctic marine mammals

This past May, sea ice in the Chukchi Sea along the northwest coast of Alaska began its annual melt and retreat earlier than ever before observed. Open water extended all the way to Barrow, Alaska, during the month. This is one of many records set over the past decade of dramatic climate change in the Arctic.

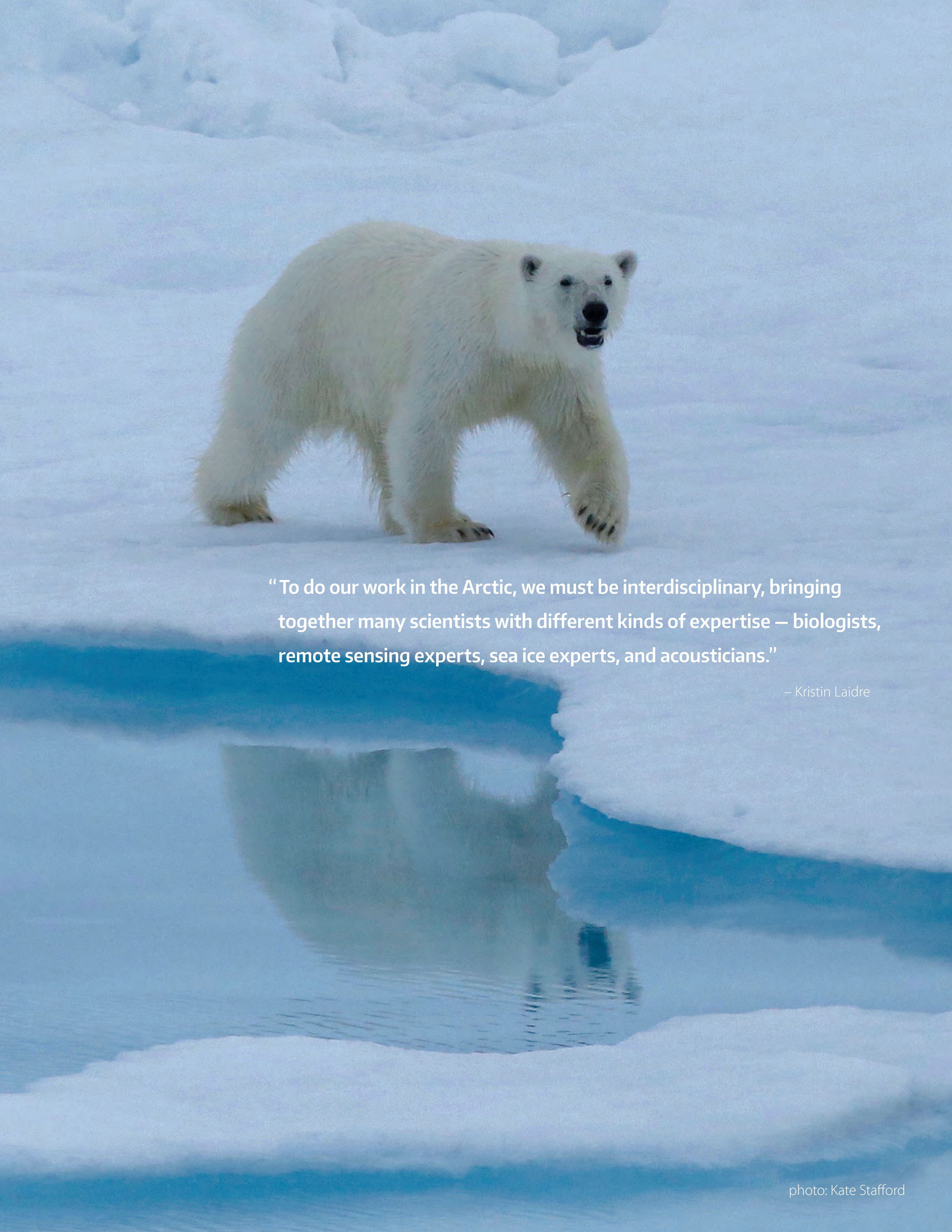
APL-UW scientists are renowned for their ability to analyze the changing air–ice–ocean system, especially the decreasing summertime extent and volume of sea ice. An ice-diminished Arctic Ocean also has wide-ranging effects on animals, whose movements coincide with annual sea ice cycles. Several APL-UW scientists, with expertise spanning many disciplines, are working to link the physics and biology of climate change in the Arctic.

There may be no greater icon of the Arctic than polar bears. Sea ice is their platform for life — they rely on it to travel, hunt, and reproduce. They cannot hunt seals on land or open water, and prefer pack ice at a concentration greater than 50 percent. With earlier ice breakup in spring, delayed freeze-up in autumn, and thinner, broken floes that are more easily blown by winds, polar bear habitat is in danger. Can this threat be measured?

Biologist **KRISTIN LAIDRE** and mathematician **HARRY STERN** used a decades-long satellite record of daily sea ice concentration to construct a clear and concise indicator of polar bear habitat health that encompasses the entire circumpolar Arctic. For each of the 19 arctic regions inhabited by polar bears and recognized by the International Union for Conservation of Nature (IUCN), they calculated the date each spring that sea ice retreated from the region, and the date each fall that sea ice advanced across the region, for every year from 1979 to the present. The trends in the spring and fall dates are indicators of how the changing climate is impacting habitat for these ice-obligated predators.

They report that now polar bears have access to good sea ice habitat for seven weeks fewer each year than they did three decades ago because of earlier retreat and later advance. “Spring and fall transitions bound the period when there is good ice habitat available for bears to feed. These periods are also tied to the breeding season and when females come out of their maternity dens with small cubs,” says Laidre. While a direct correlation between sea ice loss and bear population decline is not yet clear, the trend is not moving in the bears’ favor. Stern reasons, “If two hungry months are stretched to three because ice is slow to refreeze, the animals could be pushed beyond their survival limit.”

A key strength of the sea ice indicator of polar bear habitat is that it can be applied consistently and comprehensively across all polar bear subpopulations, from Baffin Bay to the Kara and Chukchi seas. Now the IUCN and other international organizations have adopted the indicator for polar bear population health assessments. “It’s nice to see this work being used in high-level conservation goals,” notes Laidre.



> **"To do our work in the Arctic, we must be interdisciplinary, bringing together many scientists with different kinds of expertise – biologists, remote sensing experts, sea ice experts, and acousticians."**
>
> – Kristin Laidre

photo: Kate Stafford

Beluga whales are the most abundant cetacean in the Arctic. Their spring migration northward through Bering Strait and into the Chukchi and Beaufort seas follows the spring and summer sea ice retreat. With a longer ice-free season, are belugas spending more time in the Beaufort and Chukchi seas? For some belugas the answer is yes, and for others, no.

> "One prediction of climate change is animals are going to change their seasonal presence in a region. At least one population of belugas might be adapting to rapid changes in its environment."
>
> – Kate Stafford

There are two distinct populations of Pacific Arctic belugas, the Beaufort and Chukchi. The subpopulations share geographic distributions. Marine biologist **DONNA HAUSER**, oceanographer **KATE STAFFORD**, Laidre, Stern, and their colleagues are the first to report that over the course of a decade the Chukchi belugas have shifted their fall migration later by two to four weeks, coinciding with observed delays in onset of freeze-up. Beaufort belugas, however, have not changed the timing of their fall migration.

Since the early 1990s researchers have tracked beluga movements using satellite-linked transmitters or moored hydrophones that listen underwater for their calls. These data help clarify the relationships of belugas to sea ice, as well as other oceanographic and environmental factors affecting habitat use and behavior. Both beluga populations use the western Beaufort Sea from April to early November, although timing is offset. Chukchi belugas concentrate along the continental slope and especially Barrow Canyon.

Sea ice is only one factor affecting summer–fall habitat selection, in conjunction with dynamic regional hydrography that influences the distribution and abundance of prey. This and the extended residency in preferred habitat by the Chukchi population suggests that belugas can respond quickly to ecosystem changes, but also complicates the researchers' ability to predict how they will fare in a future ice-diminished Arctic.

A range of governments and agencies are stakeholders in arctic climate science and animal conservation. Organizations sponsoring this APL-UW research are: National Aeronautics and Space Administration, National Science Foundation, National Oceanographic Partnership Program, Alaska Beluga Whale Committee, North Slope Borough and School District of Alaska, National Marine Fisheries Service, National Fish and Wildlife Foundation, Alaska Department of Fish and Game, Department of the Interior Minerals Management Service, Fisheries and Oceans Canada, Fisheries Joint Management Committee, Village of Point Lay, and Greenland Institute of Natural Resources.

photo: Kate Stafford

a glimpse into 18th century arctic climate

Mathematician Harry Stern has always been interested in historical maps. His study of the journals and maps from Captain James Cook's third voyage has pushed back the data records of summer sea ice extent in the Chukchi Sea by nearly 50 years. Cook sailed north through Bering Strait in summer 1778 searching for a northern passage to link the Atlantic and Pacific oceans. Instead he found a wall of ice near 70°N. During his search for a way through or around the ice, he plotted the earliest known charts of the summer sea ice edge in the Chukchi Sea.

Stern notes that Cook's observations of the ice edge are in accord with those made by later 19th century explorers, as well as those from the beginning of the satellite era in 1979. But after 200 years of stability, arctic climate and sea ice extent changed dramatically beginning in the 1990s. If Cook were sailing in the summertime Chukchi Sea today he would find open water hundreds of miles farther north than in 1778, allowing him to discover a navigable Northwest Passage.

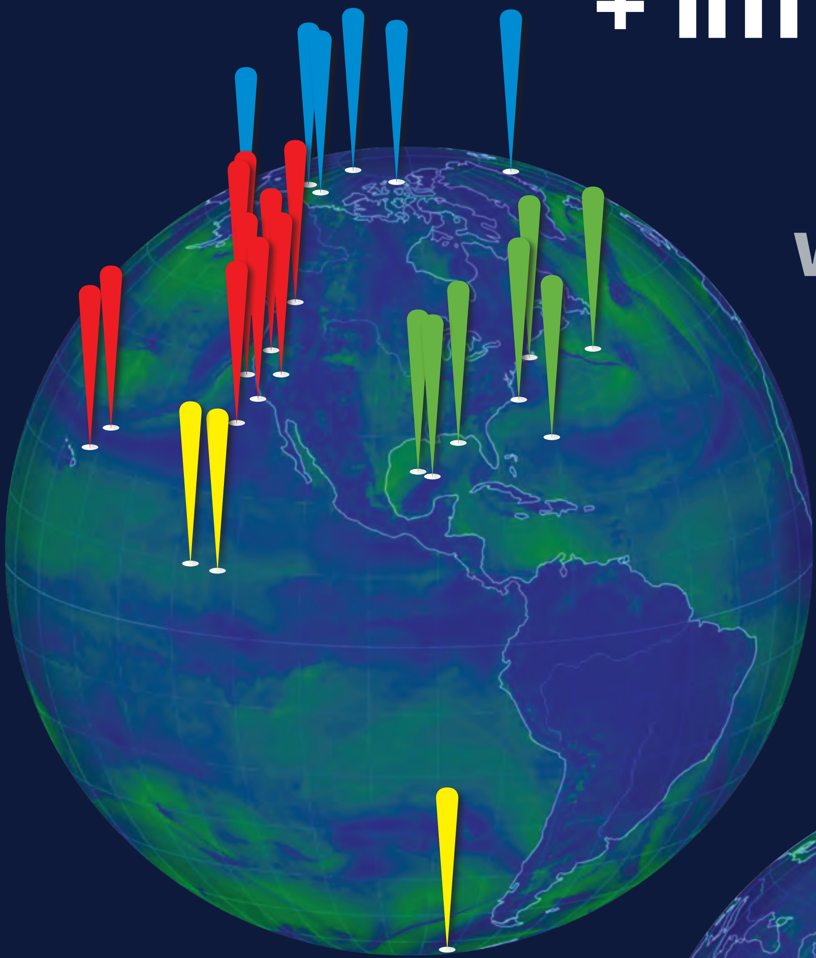
laidre a 2017 pew marine fellow

Kristin Laidre received a prestigious Pew Fellowship in Marine Conservation to support her research and public engagement on the risks to polar bears in a changing Arctic. During the three-year fellowship, Laidre will compile data from researchers and agencies in four arctic nations, developing the most comprehensive look at polar bear populations to date.

She will also conduct extensive interviews with indigenous communities in the north to understand the interacting influences of climate change and subsistence hunting. Laidre is committed to disseminating results from the research in all arctic nations to inform international conservation efforts and increase sociopolitical awareness.

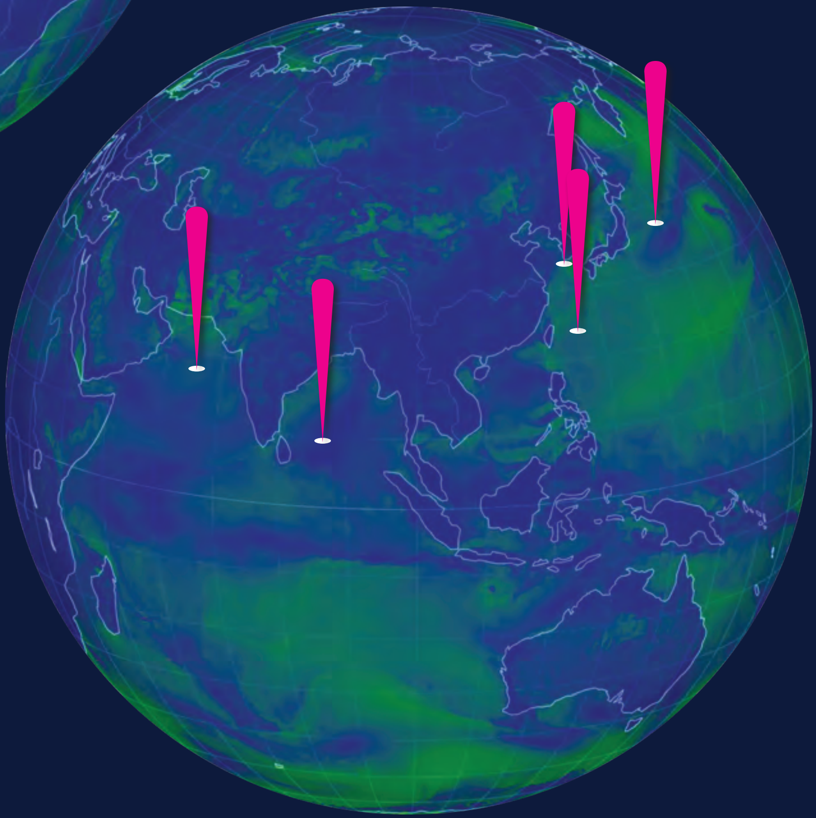
photo: Kristin Laidre

global reach + influence



where we go...

We design, build, stage, and deploy the technology needed to pursue ambitious scientific programs in the field, especially at sea. Our research endeavors take us around the globe every year.



Environmental Sample Processor on the Northwest Enhanced Moored Observatory
Ocean Observatories Initiative VISIONS '16 + '17
Wave Breaking at River Plumes
Remote Sensing in the Nearshore Zone for Improved Homeland Security
Acoustic and Environmental Measurements from Underwater Detonation Training Events
Wave Energy Buoy that Self-Deploys
Submesoscale Mixed-Layer Eddies Experiment
Waves, Langmuir Cells, and the Upper Ocean Boundary Layer
Inner Shelf Dynamics
Sensing and Simulating Spatial Snow and Streamflow in the Sierra

Sea State and Boundary Layer Physics of the Emerging Arctic Ocean
Canada Basin Acoustic Glider Experiment — CABAGE
Assessing the Impact of Small, Canadian Arctic River Flows — SCARFs — to the Freshwater Budget of the Canadian Arctic Archipelago
Wolverine Glacier Icefield-to-Oceans Experiment — Assessing Glacier Change and Downstream Impacts
Ice Exercise 2016 — Ice Camp Sargo
Polar Bear Population Assessment
Stratified Ocean Dynamics of the Arctic

North Atlantic Aerosols and Marine Ecosystems Study — NAAMES
SWIFT and EM-APEX Floats to Characterize the Surface and Upper Ocean
Impact of Breaker Type on Wave Dissipation on a Natural Beach
Consortium for Advanced Research on Transport of Hydrocarbon in the Environment
Lagrangian Submesoscale Experiment — LASER
Seabed Characterization Experiment
CLUTTEREX — Munitions Acoustics in Presence of Clutter

Salinity Processes in the Upper Ocean Regional Studies 2
Lady Amber Profiling System
Pathways of Circumpolar Deep Water to West Antarctica

Air–Sea Interactions in the Northern Indian Ocean
Storm-Forced Near-Inertial Waves and Mixing
Northern Arabian Sea Circulation — Autonomous Research
Eddies and Kuroshio Dynamics Near Taiwan
KOREX — Mid-frequency Acoustics Transmission + Reverberation

ocean observations by swarm

One-by-one, the bright yellow, finned cylinders, bristling with sensors are lowered from the ship's stern into the ocean. Then, following internal control programs, they sink slowly, in unison, to about 200 m, where they pause then slowly ascend back toward the surface with sensors firing to measure temperature, depth, salinity, currents, and turbulence. When each 90-minute excursion ends with a return to the surface, the robot's location is fixed by GPS, then the profile data and position information are transmitted back to the ship by a satellite uplink.

smile

Investigators aboard the R/V *Sikuliaq* used swarms of EM-APEX floats, shipboard sensors, and towed instruments to survey the North Pacific Subtropical Front north of Hawaii for one month in early 2017. Here, they were looking for regions of active de/re-stratification — the upper ocean adjusting in response to mixing induced by strong storms — during the Submesoscale Mixed-layer Eddies (SMILE) experiment funded by the National Science Foundation.

In the North Pacific Subtropical Front, hundreds of miles northeast of Hawaii, warm salty water flows northward over cold fresh water, with stratification on both sides of the front. APL-UW investigators and their colleagues placed arrays of EM-APEX floats into the ocean here to observe lateral processes such as interleaving. This is where two adjacent water masses with different structures in temperature, salinity, and density slide past each other to produce alternating layers originating from each side of the front.

During SMILE, the team completed deployments and recoveries of three EM-APEX swarm arrays, with 9, 16, and 23 floats profiling the upper ocean for 5, 6, and 7 days, respectively. Programming the swarm to profile in sync addresses a common problem for observational oceanographers — space–time aliasing. Measurements from the profiling swarm help them to separate the observed spatial features associated with the ship moving from one water mass to another from temporal features. This enables a rendition of the actual three-dimensional evolution of the upper ocean's structure.

Deploying the EM-APEX array and surveying with the *Sikuliaq* for about one week was sufficient to separate the lower frequency dynamics the scientists were targeting from near-inertial shear that dominates measurements on short timescales. At the first SMILE station, the floats followed a path with the mean current, and also sped up and slowed on alternating periods, as expected due to the oscillating, inertial motions

photo: Hyang Yoon, U. Hawaii

adding em to apex

EM-APEX floats were developed at APL-UW with Office of Naval Research support about one decade ago by augmenting Webb Research Corp. APEX (Autonomous Profiling EXplorer) floats with electromagnetic sensing and processing subsystems.

APEX floats vary buoyancy to profile the water column, measuring temperature, conductivity, and pressure. GPS position fixes are made while at the surface. The integrated EM subsystem determines horizontal velocity by measuring the motionally-induced electrical fields generated by the ocean current moving through the vertical component of the Earth's magnetic field. This technique was developed and perfected by Senior Principal Oceanographer Thomas Sanford during his career at APL-UW. EM-APEX floats are available commercially to the research community from Teledyne Webb Research.

The robot is a capable instrument and flexible platform for oceanographic research. Scientists use the floats to investigate upper ocean mixing, mesoscale eddies, fine structure, wind-generated internal waves, and, with air-deployment capabilities, the upper ocean response to tropical cyclones.

of the ocean. Here, the investigators expected the floats to profile across a well-defined mixed layer, but instead they encountered stratification nearly to the surface. Deeper was a section of nearly uniform water, which may have been the remnant of a previous mixed layer capped by water that had evolved over time. This signal of interleaving among pre-existing parcels of water is the type of restratification event they had planned to observe.

photo: Lucas Boland, UW

At another station, the swarm moved in a surprising and elliptical pattern about 20 to 30 km across, and after nearly 7 days, all the floats ended nearly where they had started. "This was clearly an eddy, though we weren't immediately sure what kind," notes Principal Oceanographer **JAMES GIRTON**. Typical eddies in the region are several times as large. Inspecting high-resolution satellite ocean temperature images taken during clear skies a few days earlier, Girton concluded that, "The elliptical feature was likely half of a 'dipole' or 'mushroom vortex' of two interacting eddies. The Subtropical Front is unstable, producing meanders and eddies that interact and break down into smaller features."

Based on early analyses, the SMILE data collection strategy was a success. The ship surveys and float swarms captured spatial snapshots at regular intervals, and data from each can be mapped independently and compared. "Our challenge is to understand the advection of horizontal property gradients in the upper ocean, and we know we were sampling the gradients and velocities with EM-APEX swarms," states Girton. He is confident that they captured the submesoscale (1–10 km) dynamics well, which was the primary goal. This is no small challenge because at this small scale, the rules oceanographers apply to larger-scale motions in the ocean can fall out of balance. Girton adds, "This is one reason why we needed to measure rapidly and with dense coverage."

apl-uw smile team: **ERIC BOGET, JAMES GIRTON, JOHN MICKETT, RYAN NEWELL, CHRIS SIANI,** and **AVERY SNYDER**

oil convergence + dispersion on ocean currents

How does oil spread away from a spill area? Surprising observations from a recent research cruise in the Gulf of Mexico near the site of the 2010 Deepwater Horizon disaster provide new insight.

Hundreds of small ocean drifters were released to track the motion of surface currents and act as a surrogate for oil. Instead of spreading apart, many of the drifters converged into a small area during the first week and only then spread apart slowly over the next month. “These convergence regions would be excellent places to recover spilled oil,” suggests Senior Principal Oceanographer Eric D’Asaro, who served as chief scientist on the R/V *Walton Smith* during LASER — the Lagrangian Submesoscale Experiment funded by the Gulf of Mexico Research Consortium.

In areas of drifter accumulation, Lagrangian floats were deployed to measure vertical velocities in the upper ocean. The LASER team reports that the drifters converge due to downwelling at density fronts, linking several types of observations and theoretical and modeling predictions.

photo: Eric D’Asaro

sams

The Sediment Acoustic-speed Measurement System

is a sediment penetrating instrument with a hydrophone-tipped probe and 10 acoustic sources above the water–sediment interface. This crisscrossing source–receiver arrangement measures directly the sediment sound speed and attenuation as a function of frequency and penetration depth.

For the Seabed Characterization Experiment at the 'great mud patch' on the continental shelf south of Martha's Vineyard, SAMS was deployed to depths greater than ever before. The original on-deck drilling mechanism was not feasible so APL-UW engineers designed an alternative — a two-way water pump that creates a jet or a suction force — to mount on SAMS itself. Senior physicist **JIE YANG** and the engineering team completed 18 SAMS stations, interrogating the surficial 3 m of the bottom. The surficial mud sound speed was slightly less than water with little variance across its volume and little frequency dependence.

"Using SAMS we can address some of the important aspects of sediment inhomogeneity," says Yang, "such as bottom layering structure and sound speed gradients due to sediment consolidation, which affects propagation."

The Intensity Vector Autonomous Recorder

is a new relatively small and self-contained instrument developed by APL-UW to advance underwater acoustics research. IVAR's bright red sphere houses a vector acoustic sensor that hears sound differently than a conventional hydrophone. "IVAR records sound pressure and particle velocity at a single point 1 m above the seabed, sensing the direction of the sound," according to Senior Principal Engineer **PETER DAHL**.

The ONR Seabed Characterization Experiment was IVAR's first research deployment. Safely lowered to the muddy seafloor, it was left to record autonomously for several days as acoustic signals were transmitted from research vessels nearby.

IVAR provides a more detailed picture of the sound field, such as its modal structure and how this structure is influenced by the muddy seabed.

ivar

SAMS and **IVAR** were each developed under the **Office of Naval Research** DURIP, a DoD–university partnership to support invention of instruments needed to conduct cutting-edge research.

photo: Peter Dahl

abundant ecosystems lurk deep in ocean eddies

Nearly one-third of the world ocean's surface is covered by mesoscale eddies — swirling bodies of water up to 200 km across. In the North Atlantic Ocean, eddies spinning off the meandering Gulf Stream are among the most energetic observed anywhere. Eddies can trap and transport ecosystems great distances across the open ocean as well as pump nutrients from the depths to the sunlit surface.

Oceanographer **PETER GAUBE** is collaborating in NASA-sponsored research to describe biological responses to and interactions with these oceanic weather systems. Research vessel surveys, and measurements by aircraft, satellites, and autonomous floats are being used to study the problem. There is another surprising oceanographic research platform in this mix: white sharks.

In the North Atlantic, white sharks spend long periods, sometimes an entire winter season, swimming in the open ocean. Two adult female sharks, tagged by OCEARCH with satellite positioning transmitters, have been observed to swim in circular motions during periods when they are offshore. Gaube recognized that these circular tracks were the same size as mesoscale eddies. Eddies, too, are tracked by satellites equipped with altimeters that identify the features as anomalous bulges and depressions in sea surface height.

Satellite tracking shows that the sharks swim more often inside eddies than outside, and they prefer a specific type — anticyclones. Generally, anticyclones are associated with downwelling, are warmer, and are often lower in nutrients and phytoplankton. Why would a top predator leave coastal waters with relatively high prey abundance and choose to spend so much time in these oceanic deserts? "The observations from white sharks really piqued my interest," says Gaube, and motivated him to reconcile the apparent contradiction.

OCEARCH tags keystone marine species with satellite transmitters and makes tracking data available to the science, conservation, and education communities.

photo: Robert Snow, OCEARCH

During a NAAMES cruise in early 2016, the science team targeted measurements inside and outside eddies. Satellite observations of ocean surface color reveal that higher chlorophyll concentrations occur in cyclones with their upwelling circulation that pumps nutrients up to the sunlit surface. Gaube notes that his contribution to the collaborative research "…comes a little higher up in the food chain. There are few observations of mesopelagic fish inside versus outside eddies." Previously published studies suggested that he and his colleagues would find more organisms deep in the water column in regions where higher primary production is visible at the surface. But knowing the sharks' preference for anticyclones suggested otherwise.

naames

The North Atlantic Aerosols and Marine Ecosystems Study is a five-year program of measurements funded by NASA. Four ship and aircraft campaigns plus continuous satellite and in situ oceanographic sampling by autonomous systems are used to study ecosystem variability over annual cycles, including the air–sea exchange of aerosols and gases that influence clouds and have climate implications. For his part, APL-UW oceanographer Peter Gaube is studying the dynamic mesoscale eddy field along with its associated submesoscale fronts to understand how (sub)mesoscale dynamics control the patchiness and variability of the annual phytoplankton bloom cycle as well as the distribution of higher trophic species in the open ocean.

An echosounder — a high-powered fish finder — aboard the R/V *Atlantis* for the NAAMES cruises probes the twilight zone between 200 m and 1000 m depth. Sending acoustic signals deep into the ocean and measuring the returned backscatter, Gaube characterizes the biomass — the total of organisms swimming in the 'deep scattering layer'. Echosounder measurements revealed that deep below the surface there was a lot of biomass composed in layers. In one case, backscatter strength was a factor of five higher in an anticyclone than in an adjacent cyclone. "It was very interesting to see this disconnect from what we see at the surface, what satellites observe, and what's happening at depth," Gaube notes.

Shark prey is seemingly more abundant in anticyclones; they are also warmer at depth than cyclones because anticyclonic downwelling circulation presses the warm surface layers deeper into the water column. Another tag fixed to the sharks records dive depth, duration, and water temperature. These data and observations of the vertical temperature structure of eddies made by autonomous profiling floats suggest another reason for the sharks' anticyclonic eddy preference. Gaube hypothesizes that they expend less energy on deep foraging dives in the warmer anticyclones, and may be able to remain at depth to forage for longer periods.

Intrigued by the circular tracks of white sharks swimming across the open ocean, Gaube questioned the conventional thinking about how ecosystems in the North Atlantic may be structured by mesoscale eddies and their submesoscale fronts. His work to identify, measure, and track these features helps to place in context all the point measurements taken during the NAAMES campaigns. Defining this context is a necessary step for the team as they build an understanding of basin-scale phenomena over annual cycles.

rain rain rain

APL-UW scientists and their multi-institutional collaborators spent over one month during 2016 on board the R/V *Roger Revelle* approximately 2000 miles southeast of Hawaii — one of the rainiest and most remote locations on Earth. This expedition to the intertropical convergence zone was the second in a series of research cruises to study the processes driving near-surface ocean salinity — the Salinity Processes in the Upper Ocean Regional Studies (SPURS) program.

The team deployed a series of three moorings and slipped three Seagliders and one Mixed-Layer Lagrangian Float from APL-UW into the ocean. These assets are measuring atmospheric and oceanographic variables over a complete annual cycle. A large-scale hydrographic survey, comprehensive meteorological measurements, and intensive sampling of near-surface responses to rain events were conducted from the *Revelle*. The towed Surface Salinity Profiler, which was deployed opportunistically during rainfall, profiled salinity in the upper one meter of the ocean.

Based on historical data from buoys, the team anticipated encountering a maximum of 12 rain events during the cruise, with only one strong event. In fact, they encountered 81 rain events, with 39 of them moderate and 12 strong (rain rates greater than 50 mm/hour). Total accumulation measured on the *Revelle* was 384 mm.

photo: Eric Lindstrom, NASA

wind waves current

A laboratory test tank originally built in 1975 by NASA to investigate wind–wave–current interactions is now housed at the University of Washington Harris Hydraulics Laboratory. APL-UW leadership championed the move to Seattle of the NASA Air-Sea Interaction Research Facility from its home at the Wallops Flight Facility in Virginia.

NASA decommissioned the facility in 2012 and made it available for transfer to an academic institution. After winning a nationwide competition to acquire it, APL-UW leadership built a coalition of UW units from the College of Engineering and College of the Environment, and acquired matching funds from the UW Office of Research, to raise the $400K needed to disassemble, move, and reassemble the wind–wave–current flume.

The flume is over 75 feet long, with a 40-foot-long glass test section that is 4 feet high by 3 feet wide. Its recirculating fan blows winds up to 10 m/second while a mechanical actuator produces waves and a recirculating pump drives currents to over 1 m/second. Now installed at Harris Laboratory, the facility provides UW researchers and students a robust and flexible test tank to make controlled laboratory studies of wave–current interactions and air–water gas transfer.

from idea to impact

software engineering is key

Innovative programmers at APL-UW enhance smart handheld devices used to collect data in the wake of natural disasters, order complex data streams on computer interfaces so that humans can command and control fleets of robots in distant oceans, and create the intelligence undersea vehicles need to navigate entire ocean basins without human intervention.

NATURAL DISASTERS are rare but life-threatening events. Mitigating future disasters requires research to inform the engineering of resilient infrastructure. Investigators at the UW Department of Civil and Environmental Engineering are collaborating with APL-UW software engineers in the new National Science Foundation Post-disaster, Rapid Response Research Facility (RAPID) at the University of Washington. The developers are writing new mobile software to aid post-disaster data collection in the field. The software must address all steps of the reconnaissance effort: mission planning and coordination, and data collection, transmission, and curation.

After a catastrophe such as an earthquake or tsunami, the RAPID team envisions researchers deployed to affected areas as soon as danger has passed and search and rescue efforts are concluded. Data are perishable. The condition of affected structures and landforms can change quickly.

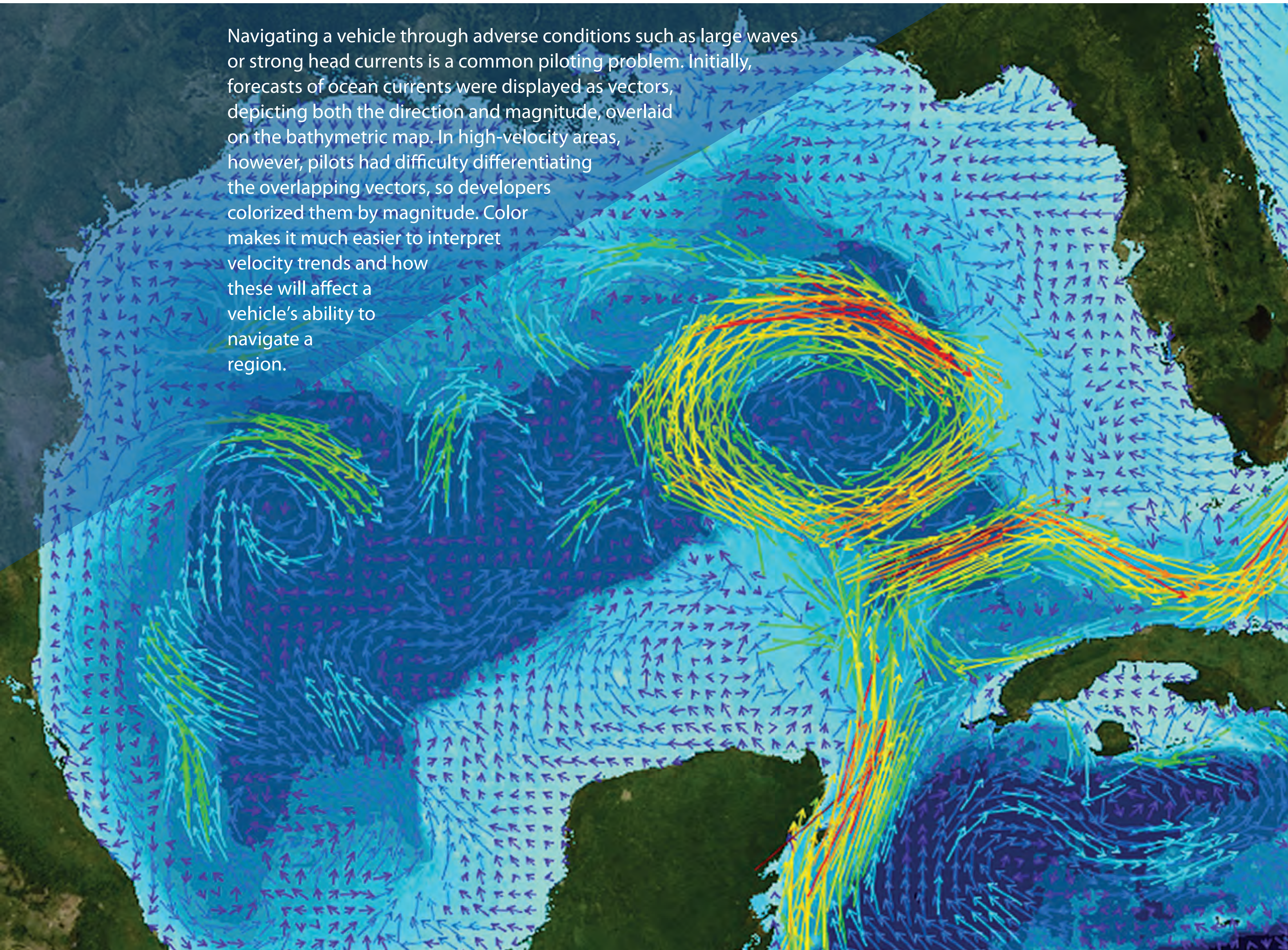
Reconnaissance missions in disaster areas require intense and ongoing planning and coordination; data collected are in various formats depending on the equipment used. To address these challenges, the team is developing a 'RAPID App'. It allows researchers to preload maps, draw anticipated routes, and assemble teams before deployment. An inventory and checklist ensures teams have the equipment and personal items needed to conduct their mission. "App development began with graduate students researching required features, then we created a range of prototypes to demonstrate how the requirements would be realized," explains Principal Engineer **TROY TANNER**.

The app provides communication and data sharing, even in areas with limited or no network connectivity. It also treats all data equally. Data are not compartmentalized by type, rather, a data model allows all types to be compared at once. This creates new opportunities to link and analyze data sets, and to discover new relationships between information that might otherwise be treated as unrelated.

ROBOTIC OCEAN-GOING PLATFORMS have transformed the U.S. Navy's collection of physical oceanographic data that are assimilated into operational models of the ocean environment. NAVOCEANO Glider Operations Center pilots command a fleet of sea-going robots every day with the help of a graphical user interface engineered by APL-UW.

For nearly a decade, pilots have used the Unmanned Systems Interface (USI) to input instructions — plan missions, adjust routes, and review and compare data from multiple platforms in a region — through a map-based web application. The USI translates pilots' commands into the inputs expected by each vehicle type and displays NAVOCEANO ocean model data. These displays help pilots analyze vehicle responses to the environment and predict future responses.

Maintaining an open, collaborative relationship with the NAVOCEANO management and pilots, APL-UW programmers continue to improve the product and experience. Where once ocean depth was displayed with bathymetric contours, now it is represented by the colors from the General Bathymetric Chart of the Oceans, and depth anywhere on the map is displayed with a point and click of the pilot's mouse.



Navigating a vehicle through adverse conditions such as large waves or strong head currents is a common piloting problem. Initially, forecasts of ocean currents were displayed as vectors, depicting both the direction and magnitude, overlaid on the bathymetric map. In high-velocity areas, however, pilots had difficulty differentiating the overlapping vectors, so developers colorized them by magnitude. Color makes it much easier to interpret velocity trends and how these will affect a vehicle's ability to navigate a region.

As new platforms have been added and pilots command a greater number simultaneously, USI engineers have found ways to lessen the interactive burden. Glider Observation Strategies (GOST) software, which runs on the NAVOCEANO mainframe supercomputer, automates the planning of undersea glider tracks. In a two-way conversation, the USI forwards to GOST a message with the vehicle's location, speed, and profile depth after each dive sequence. GOST plans are returned to the USI. Pilots see a comparison of possible mission trajectories and waypoints based on forecasts of local ocean currents. Trajectories also show the relative value of the oceanographic data along the route for the forecast model, empowering pilot decision making.

The Unmanned Systems Interface automates information exchange across platforms, and among the pilots, the ocean-going robots, and supercomputing resources.

NEW SENSORS AND PROCESSING ALGORITHMS for Seaglider are extending its autonomous navigation capability. A goal of an APL-UW science and engineering team is to drop a glider through a hole in the sea ice to survey an entire ocean basin without satellite contact or human intervention.

In temperate seas the glider typically surfaces at the end of each dive to get a GPS position fix and make a satellite connection to relay data and receive new commands. In ice-covered seas that prohibit surfacing and GPS coordination, Seaglider navigates by processing signals from underwater acoustic beacons that are either fixed or that have GPS and can encode and transmit their own locations. Transects of the ice-covered Davis Strait have been made for the past decade with the aid of moored acoustic sources with a navigational range of about 100 km.

Greater ranges were achieved — routinely to 100 km and occasionally to over 400 km — in the Beaufort Sea marginal ice zone by equipping Seaglider with a low-frequency Micromodem, developed at the Woods Hole Oceanographic Institution, to capture low-frequency acoustic transmissions and by exploiting a well-defined sound channel that exists in the Beaufort.

In the Canada Basin Acoustic Glider Experiment, the APL-UW team and collaborators from WHOI and the University of Rhode Island are pushing the limits of long-range, under-ice geolocation. Two Seagliders were deployed in the Beaufort Sea last summer to survey a region bounded by a tomographic array of six acoustic transceivers arranged pentagonally with a radius of 150 km.

At four-hour intervals, Seagliders received the incoming signals from the transceivers. The Micromodem produced time-of-arrival estimates that are used by the glider navigation code, along with the known times of signal transmission and an estimated sound speed through water, to calculate a range from each source. This method works well at short ranges, but at longer ranges the intervening ocean environment distorts the acoustic arrival pattern, which can lessen the accuracy of the glider's position estimate.

apl-uw rapid team: **ROBERT CARR, ALEX DIOSO, DANIEL STROMECKI,** and **TROY TANNER**

apl-uw usi team: **PETER BRODSKY, ROBERT CARR, ALEX DIOSO, DAVID JONES,** and **TROY TANNER**

apl-uw cabage team: **JASON GOBAT , BENJAMIN JOKINEN, CRAIG LEE, ANDREY SHCHERBINA, GEOFF SHILLING,** and **SARAH WEBSTER**

To address this, processing capabilities are being developed to use the sound speed profiles Seaglider collects along its mission path to model the environmental conditions between the source and the glider's current position. Iterations between this model and new navigation algorithms that account for the glider's horizontal and vertical motion through the water column as it receives the navigation signals further refine the range estimate and thus the glider's position estimate.

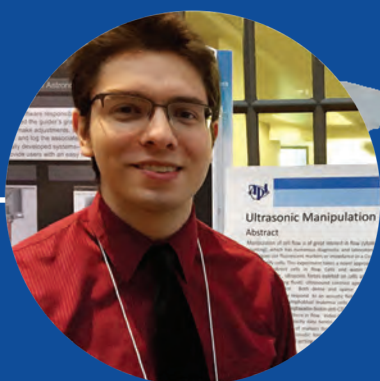
During CABAGE, Seagliders also flew for the first time with acoustic Doppler current profilers to measure overlapping current profiles as the glider descends and ascends. "Incorporating shear measurements into the glider's positioning algorithm is complicated by Seaglider's own motion and the lack of a GPS signal subsea," explains Senior Engineer **SARAH WEBSTER**. "This hasn't been done before on Seagliders, so it's a lot of fun to work together to figure out all the complexities of integrating the ADCP processing with the glider's navigation."

With the ADCP measurements, the team is working to produce high-resolution shear and current profiles throughout the glider's dive in near-real time. These high-resolution data are of great scientific value, and are also used by the glider's navigation algorithms to account for how the glider is pushed around by the currents, providing a more accurate estimate of the glider's position subsea, especially during intervals between navigational source transmissions.

photo: Ben Jokinen

future generations
of scientists + engineers

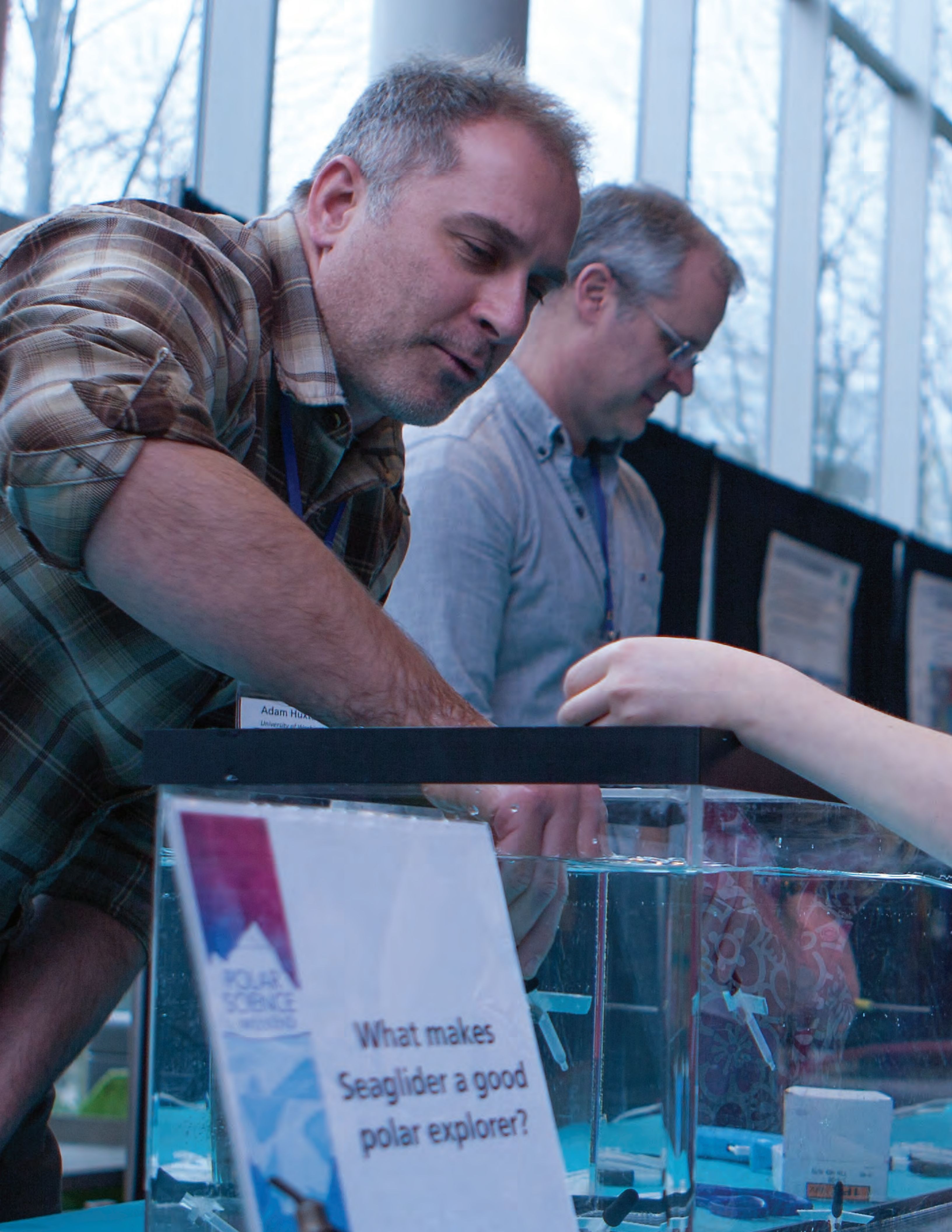
The Applied Physics Laboratory advances the education mission of the University of Washington by teaching, advising, and mentoring students.



APL-UW scientists guided the advanced degree programs of 20 students to completion over the past biennium. Scores of UW undergraduate and graduate students every year are integrated directly into sponsored Laboratory research projects, where they gain specialized training, experience, and broad professional support.

Under the guidance of APL-UW principal investigators, postdoctoral scholars find support from the two-year SEED fellowship, where they can define their career goals and establish an independent research program.

Beyond the UW, Laboratory staff share science with the community — inspiring early learners with hands-on activities, and motivating middle and high school students to pursue studies in STEM fields.


POLAR SCIENCE
What makes Seaglider a good polar explorer?

polar science weekend @ pacific science center

Hands-on activities, live demonstrations, and interactive exhibits engage young learners with cool science at the annual three-day event in downtown Seattle. The successful partnership of the Pacific Science Center — the most visited museum in Washington — and the Laboratory is in its twelfth year.

Students, with their teachers, friends, and families, learn face-to-face from scientists who work in some of the most remote and challenging environments on Earth. They test their taste buds to differentiate the saltiness of the Arctic Ocean from other seas, build and launch tiny models of buoyancy-driven gliding robots, and clock mock glacial flow.

In 2017 over three dozen APL-UW staff were among the nearly 180 total volunteers bringing polar science to life for thousands of visitors.

A highlight for many undergraduate students mentored by APL-UW scientists is to prepare and present posters and talks for the annual University of Washington UNDERGRADUATE RESEARCH SYMPOSIUM. In its 20th year, the May 2017 event showcased the work of over 1200 motivated researchers.

cultivating research skills

Two students presented on topics at the intersection of engineering and medical therapies. The ability to sort and count cells in a fluid volume is important in diagnostic and therapeutic medical applications. Junior engineering major **DINO DE RAAD**, advised by **TOM MATULA**, studied methods to increase the efficiency and effectiveness of flow cytometry. His novel approach uses ultrasonic waves to sort and count cells in a flow. By conjugating the target cells with an ultrasound contrast agent (lipid-shelled microbubbles), he showed that the marked cells can be redirected preferentially by an acoustic radiation force.

Junior engineering major **ALYSSA SCHUL** pursued a research project in mentor **DANIEL LEOTTA**'s lab, where they are developing a simulation system for healthcare professionals to improve their ability to classify patients' vascular disease severity with duplex ultrasound scanning. Her presentation recapped her use of MATLAB to create the virtual three-dimensional vessel image volumes that are the foundation for vessel reconstruction and computer simulations. She detailed how applying image correcting algorithms can minimize sampling artifacts and enhance vessel alignment in the simulator.

ELIZABETH MARIE FARRELL, a senior astronomy and physics major, and advisor **TIM ELAM** are perfecting an instrument that will fly to Mars in 2020 to search for evidence of past life. Elam is on a team that developed an X-ray fluorescence spectrometer for the Mars rover that bombards surface materials with high-energy radiation to probe their elemental composition and spatial distribution. Instrument tilt from the surface attenuates the high-energy beam. At the symposium Farrell presented results of her laboratory experiments, where spectra of standard materials were compared with measured spectra from the same materials at various tilt angles. Results will be applied where they can improve the instrument's computer code that compensates for tilt effects.

enrichment for STEM-motivated girls

Engineers **TRINA LITCHENDORF** and **DANA MANALANG** created and led interactive workshops on the science and engineering of ocean observing systems for 45 middle and high school girls. As part of a local *Expanding Your Horizons* annual conference to increase girls' access to women in STEM careers, Litchendorf and Manalang shared their expertise gained as members of the development and deployment teams on the Ocean Observatories Initiative Cabled Array off the Pacific Northwest coast.

> "We introduce the girls to the practice of engineering and give them a hands-on experience with oceanographic instruments and methods. Our aim is to empower and inspire girls to pursue careers as ocean scientists and engineers."

The students listened to a presentation on the array's scope and purpose, the variety of instruments deployed, and how measurements are used to study underwater volcanos, ocean chemistry and circulation, and marine organisms. Then they examined the hybrid fiber-optic/electrical cable that laces the array together.

Litchendorf and Manalang devised an experiment where the students used a Sea-Bird Electronics MicroCat C-T recorder to measure temperature and conductivity in various water samples. Small groups formed to calculate respective densities of each sample and then they compared their findings. The workshop culminated with a discussion led by the engineers on how waters of differing densities interact and control ocean circulation.

mentoring student engineers

The UW Human-Powered Submarine Team has been active for over 20 years as a student club in the UW Department of Mechanical Engineering. Every year the team designs and builds a submarine to compete in the alternate-year International and European Submarine Races. APL-UW Principal Engineer **ANDY STEWART** serves as the team's faculty advisor.

The UW's entry in the first human-powered sub competition in 1989 was built at APL-UW and the team was comprised of Laboratory staff and UW students. With Stewart advising the club, many of the design and build activities have now returned to APL-UW facilities.

"They have to learn how to make something that's robust and flexible, and how to adapt and problem solve quickly in the heat of competition," notes Stewart.

Taking inspiration from the 1989 sub that was constructed of spruce strips coated by a fiberglass shell, the team collaborated with craftspeople at the Northwest School of Wooden Boatbuilding for their latest model. The two-person sub's hull uses red cedar strip planking and fiery khaya veneer.

photo: Andy Stewart

student achievements

We recognize with pride in every *Biennial Report* the graduate students who earned advanced degrees and the APL-UW scientists who served as their research and thesis advisors.

BRIAN CHINN, Oceanography, Ph.D., 2015
On the structure of the internal wave field: The impact of the distribution of shear and strain variance in wavenumber-frequency space on mixing estimates
James Girton

SARAH DEWEY, Oceanography, M.S., 2015
An edge-referenced surface fresh layer in the Beaufort Sea seasonal ice zone
James Morison

HAYLEY DOSSER, Oceanography, Ph.D., 2015
Internal waves in the western Arctic Ocean
Luc Rainville

ERICA ESCAJEDA, Aquatic + Fishery Sciences, M.S., 2016
*Identifying shifts in maternity den phenology and habitat characteristics of polar bears (*Ursus maritimus*) in Baffin Bay and Kane Basin*
Kristin Laidre

NAVID FARR, Bioengineering, Ph.D., 2015
MRI-guided focused ultrasound application for targeted drug delivery
Joo Ha Hwang

EMILY KALAH GADE, Political Science, Ph.D., 2017
Connection and resistance: Civilian experiences of violence in conflict zones and their impact on civilians' political preferences for violent and non-violent resistance
Michael Gabbay

DONNA HAUSER, Aquatic + Fishery Sciences, Ph.D., 2016
Beluga whale distribution, migration, and behavior in a changing Pacific Arctic
Kristin Laidre

BYRON KILBOURNE, Oceanography, Ph.D., 2015
Oceanic variability near the Coriolis frequency: Generation mechanisms, observations, and implications for interior mixing
James Girton

NING LI, Statistics: Advanced Methods + Data Analysis, M.S., 2015
Sensitivity analysis
Caren Marzban + Scott Sandgathe

PAUL MURPHY, Mechanical Engineering, M.S., 2015
Estimation of acoustic particle motion and source bearing using a drifting hydrophone array near a river current turbine to assess disturbances to fish
Peter Dahl

CAMILO PEREZ, Bioengineering, Ph.D., 2015
Characterization of ultrasound pressure fields, microbubbles and their interaction
Thomas Matula

KRISTIN POINAR, Geophysics, Ph.D., 2015
The influence of meltwater on the thermal structure and flow of the Greenland Ice Sheet
Ian Joughin

THOMAS POWERS, Electrical Engineering, M.S., 2016
Constrained robust submodular sensor selection with application to multistatic sonar arrays
David Krout

MICHAEL SCHWENDEMAN, Civil Engineering, Ph.D., 2016
Breaking waves on the ocean surface
Jim Thomson

ANDREW SHAO, Oceanography, Ph.D., 2016
The response of thermocline ventilation to variability at the ocean surface from observations and offline tracer modeling
Sabine Mecking

DANIEL SHAPERO, Applied Mathematics, Ph.D., 2017
Data assimilation problems in glaciology
Ian Joughin

MADISON SMITH, Civil Engineering, M.S., 2016
Surface waves in the Beaufort Sea
Jim Thomson

CHRISTOPHER STRICKLAND, Earth + Space Sciences, Ph.D., 2015
Wave propagation modeling and inversion using frequency-domain integral equation methods
Robert Odom

STEVEN T. ZECH, Political Science, Ph.D., 2016
Between two fires: Civilian resistance during internal armed conflict in Peru
Michael Gabbay

SETH ZIPPEL, Civil Engineering, Ph.D., 2017
Wave breaking in the presence of sheared currents and sea ice
Jim Thomson

the science + engineering enrichment + development

postdoctoral fellowship program supports aspiring investigators as they establish their professional careers. Two fellowships are available every year. SEED fellows pursue research goals aligned with APL-UW areas of expertise and are mentored by a principal investigator.

To describe her research interests most broadly, **WU-JUNG LEE** studies the use of sound by humans and animals to observe and understand their environment. As an acoustical oceanographer, she develops and applies active acoustic sensing techniques to probe the ocean interior. And her studies of animal echolocation — a closed-loop sensorimotor feedback system — inform how human acousticians might behave adaptively and process uncertainty to solve active acoustic sensing problems.

> "The SEED fellowship program provides the flexibility I need, because my research spans multiple traditional disciplines – physics, engineering, and biology."

Her recent studies of bat navigation and foraging behaviors involved lab experiments and computational analysis, where the goal was to create a bat-centered view of the environment, "…even though we don't know what kind of signal processing they are using," says Lee.

During her fellowship, she is collaborating with UW computer scientists and engineers to discover the interactions of marine organisms in the open ocean from sonar sensing systems. There is a continuous stream of data from echosounders on the Ocean Observatories Initiative Cabled Array that probe the full water column. Lee is using machine learning techniques to interpret echo features and identify marine organisms. The goal is to parse the incoming sonar data into biologically meaningful groups, for example, the predator–prey interactions of a fish–zooplankton assemblage. Lee adds that, "These data, and the adaptive processing tools to interpret them, provide an unprecedented opportunity to study long-term trophic interactions in marine ecosystems."

The weather systems of the ocean — meandering fronts and swirling eddies — distribute nutrients and drive primary production. In a study of elephant seals in the Southern Ocean, **ALICE DELLA PENNA** discovered that meanders and eddies also influence the movements of these top marine predators, even though they swim much faster than the currents. Though seals may cross hundreds of kilometers to forage, they drift along with the currents while they are diving most intensively to find prey.

This area of inquiry — the concentrated co-location of different organisms and food web interactions in the open ocean — is the focus of her fellowship research. Della Penna explains: "After having worked on large animals that can be tracked with satellite transmitter tags and phytoplankton that appear on satellite images of ocean surface color, I became curious about how these ocean weather systems affect zooplankton and micronekton, the intermediate trophic levels that are important links in marine food webs." With her mentor **PETER GAUBE**, she is examining the acoustic data collected during the first two North Atlantic Aerosols and Marine Ecosystems Study (NAAMES) cruises to relate the distribution of acoustic backscattering at depth — indicating zooplankton and other tiny swimming organisms — to other biological and physical datasets collected on the cruises.

Della Penna says that the project is a good fit for her overall scientific motivations. "It speaks to my interest in innovative ways to observe the ocean, through bio-logging, acoustics, autonomous sampling, and remote sensing." And she learned how to run the acoustic sampling system — a very powerful fish finder — to collect more data during the third and fourth NAAMES cruises.

photo: Emmanuel Boss

Atmospheric scientist ELIZABETH THOMPSON arrived at APL-UW last year amid preparations for a six-week field experiment in the tropical eastern Pacific Ocean.

photo: Leah Trafford

One of **CAITLIN WHALEN**'s goals during her SEED fellowship at APL-UW is to fulfill a need for the oceanographic community. She is working to construct a public data product of ocean mixing based on observations that can be compared with the output of global numerical models. "There is no global observationally-based mixing data set, so I'm combining the Argo profiling float data product from my thesis work with another public data set so that the final product has near-global coverage from 250 m depth to the bottom," she explains.

Even for oceanographers addressing questions posed on regional and global scales, small-scale turbulent mixing is important. For her thesis research, Whalen used the global Argo array of profiling floats to calculate hundreds of thousands of turbulent mixing values in the global ocean. Her work revealed that average turbulent mixing varies over multiple orders of magnitude and exhibits distinct spatial patterns across all oceans.

"The modeling community is beginning to include spatially variable mixing in global climate models, which changes the models' behavior significantly," explains Whalen. She hopes an empirical global ocean mixing product will be used to improve these parameterizations, deepening insight into the effects of spatially variable mixing on large-scale ocean processes.

During her fellowship, Whalen has joined several research cruises and sought mentoring by several investigators. "I've had the opportunity to work with **ERIC D'ASARO**, and am now working with **KYLA DRUSHKA** and **PETER GAUBE**." She cites the benefits of her fellowship so far as, "The freedom to shape my own research program and the resources available at the Laboratory and University."

"SEED is a great opportunity to create collaborative projects with APL-UW scientists and engineers that could extend well beyond my fellowship."

Thompson joined her mentors, oceanographers **KYLA DRUSHKA** and **WILLIAM ASHER**, on the NASA-funded Salinity Processes in the Upper Ocean Regional Studies cruise aboard the R/V *Revelle*. She will be analyzing measurements of upper ocean salinity in the context of satellite and radar weather data.

In the tropical eastern Pacific, rainfall usually occurs in strong bursts, leaving behind puddles of fresh water on the sea surface. At sea the SPURS team encountered various weather conditions and made comprehensive atmospheric and oceanographic observations. During her fellowship period, Thompson is using these observations and several satellite meteorological datasets to investigate how the spatiotemporal variability of individual rain events contributes to freshwater accumulation, mixing, and long-term storage in the ocean. She notes, "As I gain greater understanding of the physical processes at the air–sea interface, I also want to determine how well these processes can be estimated from satellite measurements."

Research excellence requires more than scientific rigor. Elizabeth participates in the Environmental Fluid Mechanics Group at the UW Department of Civil Engineering, and helped found a weekly 'coffee hour' that brings together women postdocs in atmospheric, oceanographic, and fisheries sciences to share knowledge and support. Thompson adds, "My advisors have been honest and transparent about the challenges of a career in research, and I am now much more prepared to lead my own programs and contribute to collaborative work."

publishing productivity

2016 contributions to the scientific + technical literature

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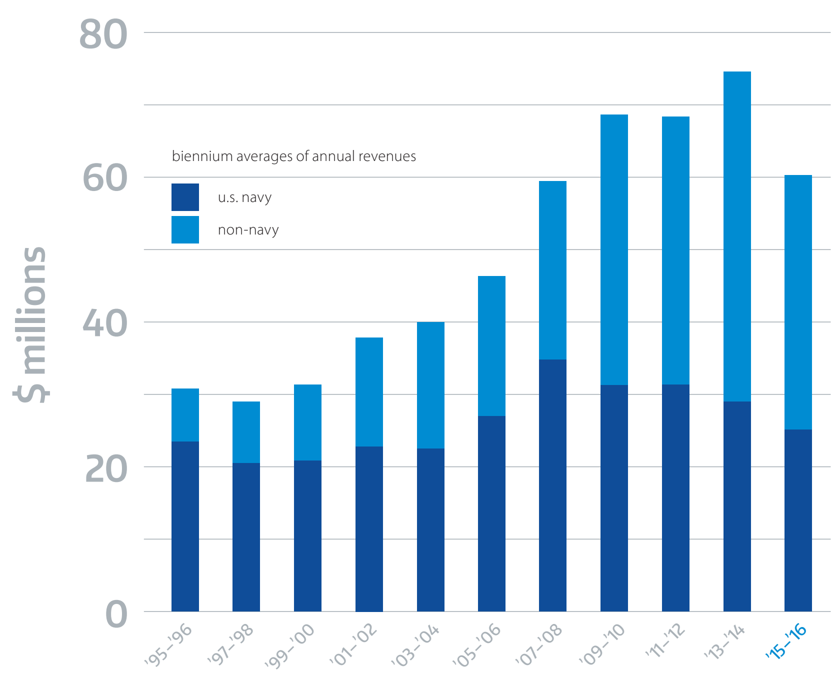
financial health

Grant and contract awards received by the Applied Physics Laboratory for this latest biennium, comprised of Federal Fiscal Years 2015 and 2016, totaled $120.4M, a reduction from the previous, record-breaking biennium. Funding was unusually weak in the first four months of FFY 2015, primarily due to fears of sequestration and federal budget delays, which negatively affected the overall funding for the biennium. Funding in FFY 2016 was strong and comparable to any of the Laboratory's best years. Prolonged reductions and uncertainties in federal research budgets and delays in research funding could have negative impacts on the Laboratory in coming years.

Strong and stable funding is driven by the U.S. Navy's and federal government's high regard and demand for the Laboratory's scientific discoveries, technological innovations, and service to the national defense enterprise.

APL-UW continues to diversify its funding portfolio. Though the Navy's proportion of total funding is less today, the Laboratory remains strongly committed to addressing the needs of the U.S. Navy, our primary customer for more than seven decades. For the latest biennium, the Navy accounted for 42% of total grant and contract funding for APL-UW. Within the Navy, the Office of Naval Research was the single largest sponsor of research and development, accounting for 24% of total grant and contract revenues. Other noteworthy Navy sponsors included the Naval Surface Warfare Center, Naval Facilities Engineering Command, and Arctic Submarine Laboratory.

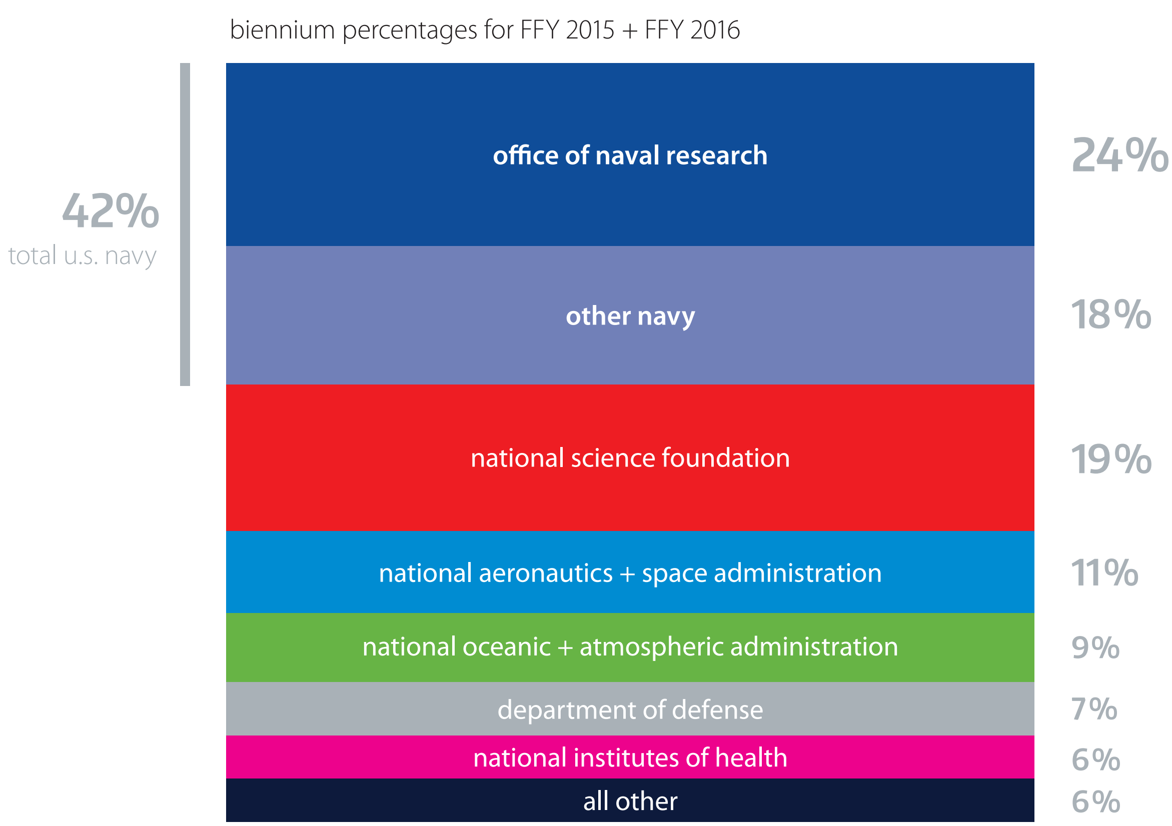


The National Science Foundation, National Aeronautics and Space Administration, National Oceanographic and Atmospheric Administration, and (non-Navy) Department of Defense remained significant research sponsors during the past biennium, providing 19%, 11%, 9%, and 7% of total Laboratory funding, respectively. Over the last quarter century, non-Navy research sponsorship has grown from 8% to 58% of total funding, which has increased the Laboratory's overall funding stability and opportunities for growth.

For this latest biennial period, the distribution of funding between basic (fundamental) research and more applied research (including development) was 63% and 37%, respectively. This distribution stands in clear contrast to the distribution a quarter-century ago, when it was 28% and 72%, respectively, and applied programs dominated. The current balance, which leans toward basic research, reflects stronger opportunities for growth and innovation in important fundamental research areas.

Averaging annual funding revenues over five-year intervals, the longest duration of any APL-UW grant, smooths the year-to-year fluctuations and better exposes the overall trend in Laboratory funding. Averages of annual revenues for the five-year periods ending with FFY 1991, 1996, 2001, 2006, 2011, and 2016, show increasing mean levels of $24.19M, $30.33M, $30.55M, $43.22M, $63.18M, and $69.11M, respectively.

For the last quarter-century there are positive trends: between 1991 and 2001 APL-UW grant and contract revenues increased 26% over the decade; between 2001 and 2011 revenues more than doubled, with an impressive increase of 107% over the decade; and between 2011 and 2016 funding continued to grow, but at a reduced pace of 9% over five years. This long-term increasing trend in funding shows that APL-UW evolved its business model successfully in the post-Cold War era.



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Sadly, I note the passing of Russell Light in 2017, who led our Ocean Engineering Department for many years. His dedication, attention to detail, work ethic, and leadership over a 35-year career at the Laboratory set an example for us all, and will be missed.

– Jeff Simmen

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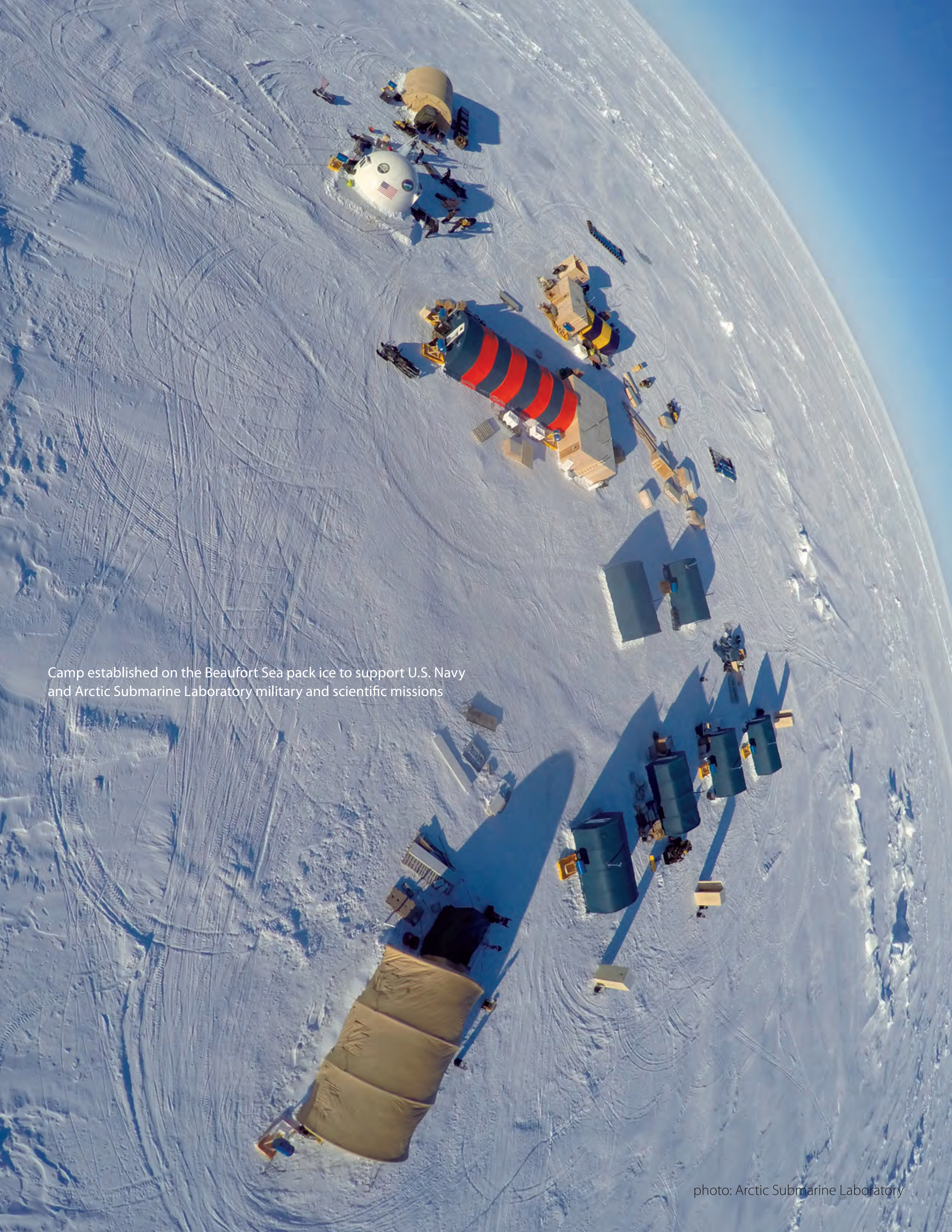
TIMOTHY E. PETERS
Vice President/Program Manager
Boeing Defense, Space + Security

PAUL E. SPEER
Chief Operating Officer
Marine Biological Laboratory



Camp established on the Beaufort Sea pack ice to support U.S. Navy and Arctic Submarine Laboratory military and scientific missions

photo: Arctic Submarine Laboratory

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