2015

Biennial Report

Applied Physics Laboratory
University of Washington

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discovery + impact

The past biennium has been productive for the Applied Physics Laboratory of the University of Washington, with many noteworthy accomplishments across our core areas of research and development. APL-UW continues to excel in advancing marine science, often by developing state-of-the-art technologies to make novel and informative measurements. The close cooperation between science and engineering is a prominent APL-UW strength and is evident in the sampling of research endeavors described in this *2015 Biennial Report.*

"The close cooperation between science and engineering is a prominent APL-UW strength."

Since our last report, APL-UW investigators have made promising discoveries in therapeutic medical ultrasound, developed innovative methods and models in acoustic and electromagnetic sensing, enhanced a real-time marine monitoring network for the Puget Sound region, performed cutting-edge engineering to advance undersea fixed and mobile systems for ocean surveillance, and pursued new lines of research in important fields where the Laboratory can contribute, such as marine hydrokinetic energy. There has been a rise in scientific activities in the Arctic due to growing interest in the region's rapidly changing and complex ocean–ice–atmosphere system. And the Laboratory is supporting, in new and greener ways, the U.S. Navy's submarine under-ice exercises in the Arctic.

Laboratory productivity remains high as measured in *knowledge transfer*, through scientific publications and presentations, and *technology transfer*, through transitions directly "into the fleet" and through commercialization. During the past biennium our number of publications in the peer-reviewed literature increased, with several articles featured or listed as "top ten most read" in scientific journals or appearing in *Nature* and *Science*. Over this period we also had a record number of patent applications and spinoff companies.

APL-UW investigators execute an impressive number of major field programs every year, collectively spanning the globe. Many of these recent field efforts were large and complex undertakings; for example, the wet-end engineering and installation of an ambitious cabled-to-shore ocean observatory in the northeastern Pacific Ocean was completed successfully, and APL-UW researchers led a multi-investigator field study of the seasonal evolution of the marginal ice zone in the Arctic.

I am proud of the recent recognition of our researchers' achievements; one of our scientists was elected to the National Academy of Sciences, a fellow scientist was named one of Seattle's "most influential people," and Laboratory engineers received commendation by the Department of Defense. Research funding for the FFY2013–2014 biennium was unprecedented for the Laboratory, with grant and contract revenues averaging $74.3 million per year.

"APL-UW science and technology has real and relevant impact, supporting regional economic growth, national defense, and a deeper understanding of the global marine environment."

APL-UW researchers' strong collaborative ties continue locally on the University of Washington campus through joint academic appointments, and nationally and internationally by leading and participating in many multi-institutional research initiatives. Over the past two years we have made special efforts to improve connectivity with industry. In our recently formed **Collaboratory at APL-UW,** we team with industry partners in a common workspace to advance research and development together. The launch of *Cyclops*, a new five-person submarine, is a fine example of comprehensive systems engineering benefiting from a Collaboratory partnership.

APL-UW continues to position itself strategically for the future. Our primary focus now is recruitment, resulting from a critical need to replenish researchers in our traditional fields of investigation, as well as a strong desire to open up new and complementary areas of research. I can report that in the past two years several exceptional scientists and engineers have joined the Laboratory.

APL-UW science and technology has real and relevant impact, supporting regional economic growth, national defense, and a deeper understanding of the global marine environment. Our successes and accomplishments are derived from the talent, innovation, and hard work of the Laboratory staff and from the confidence and strong support of our federal sponsors, especially the U.S. Navy (predominantly the Office of Naval Research) and the National Science Foundation.

Jeff Simmen

what we do...

advance scientific discovery + invention

enhance national security

educate future generations of scientists + engineers

APL-UW serves society by contributing new knowledge and technology to the national defense enterprise, industry, public policy makers, and academia. Established in 1943 at the request of the U.S. Navy, we have provided continuous access to the highest levels of academic expertise in scientific research and engineering to address Navy-specific problems.

The Laboratory's broad and deep experience in undersea science and technology is a significant reason why APL-UW is one of only five Department of Defense-designated University Affiliated Research Centers (UARCs) having long-term, large-scale, formal connections to the U.S. Navy. 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.

the emerging arctic ocean

observations + outlook

Arctic sea ice in summer has been retreating, thinning, and weakening for several decades and some scientists are forecasting an 'ice-free' season in the decades to come. One feature of the decreased summer ice extent is the retreat of the ice edge from the coast and continental shelves. This evolving boundary between open water and pack ice — **the marginal ice zone (MIZ)** — has long defined the coastal Chukchi and Beaufort seas during summer. But now the northward retreat of the MIZ and spread of open water reaches the deep Beaufort Sea each summer.

The implications of the dramatic recent changes in the Arctic are clear to the U.S. Navy — expertise in under-ice operations must be extended to the surface. Recognizing that a MIZ sweeping across deep ocean basins and increased open water in summer will change how pack ice breaks up and melts, the Office of Naval Research launched the Marginal Ice Zone Departmental Research Initiative.

This international, multi-institutional effort is designed to understand the physics of sea ice breakup and melt around the pack ice edge and how ocean—ice—atmosphere interactions might change in a summertime Arctic with large expanses of open water. While snow and ice reflect solar radiation, the dark ocean absorbs it, and this warming further speeds sea ice melt. How might other aspects of ocean–atmosphere interactions change with diminished sea ice? Do winds acting on open water produce more and larger surface waves that accelerate the breakup and melt of floes? Is there more ocean mixing in regions with partial or no ice cover?

An ONR DRI complement to the MIZ initiative is the **Sea State and Boundary Layer Physics of the Emerging Arctic Ocean**. Chaired by **JIM THOMSON**, the science team focused on Arctic Ocean conditions in early fall — the season of strongest storms and maximum open water. Observations from an intensive research cruise in October–November 2015 will be augmented by satellite remote sensing and long-term mooring data to capture air–sea–ice interactions and the exchange of heat and momentum. Much of the Arctic Ocean in summer may soon resemble a marginal ice zone. Safe and secure operations will rely on improved forecasts of weather, sea state, and sea ice.

"This is the largest experiment of its kind. Nothing like it has ever been done in the Arctic Ocean."

– ONR Program Manager Martin Jeffries

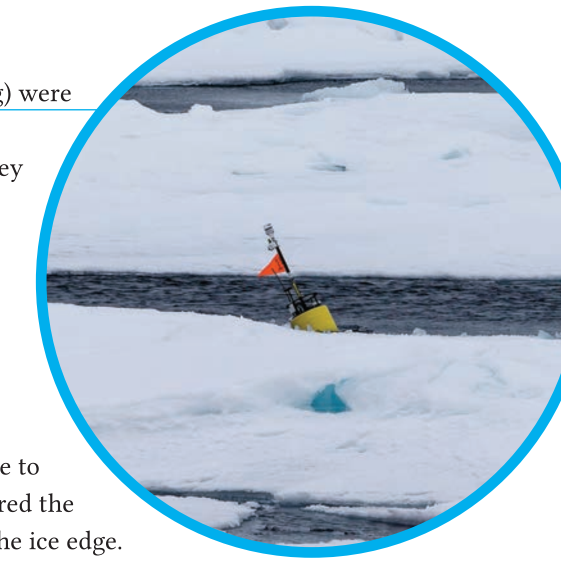
apl-uw miz research team

Alex de Klerk
Suzanne Dickinson
Jason Gobat
Adam Huxtable
Jim Johnson
Ben Jokinen
Craig Lee
Mike Ohmart
Luc Rainville
Kay Runciman
Axel Schweiger
Madison Smith
Margaret Stark
Mike Steele
Harry Stern
Joe Talbert
Jim Thomson
Sarah Webster
Jinlun Zhang

Throughout much of 2014 APL-UW researchers and their collaborators from over one dozen international institutions collected a benchmark dataset from the Beaufort Sea MIZ. They captured an amazing picture of the region from the completely frozen period in March, through melt, breakup and retreat during summer, and right through to the fall freeze-up. Science Steering Team Chair **CRAIG LEE** notes, "The physics of the MIZ involves a complex interplay among ocean, ice, and atmosphere. No one research group or instrument can measure everything we need to know, which is why this experiment involves so many researchers and platforms. The real value comes from the team working together to integrate the observations."

Continuous measurements in the harsh, remote environment necessitated an approach based on remote sensing technologies and fleets of mobile, robotic instruments that maintained an observational presence in, under, and around the sea ice over many months. Sampling began using aircraft and by establishing short-term ice camps to deploy an array of ice-based platforms along a line that stretched northward from Alaska's coast out to 400 km in the Beaufort Sea. These included ice mass balance and wave buoys, weather stations, ocean profilers, and ocean flux buoys. Then in early summer and during the breakup of the pack ice, small vessels were used to launch drifting and mobile robotic platforms within the matrix of instruments still fixed in the ice.

SWIFTs (Surface Wave Instrument Float with Tracking) were placed in open water, then deeper and deeper into the floes of the MIZ to measure how waves attenuate as they travel through the zone. "We want to understand how the ice damps, mutes, and blocks wave propagation, and how waves affect the ice; that is, how far into the pack waves penetrate, how they flex, fracture, and break the ice," says **JIM THOMSON**.



Liquid Robotics Wave Gliders, instrumented with meteorological sensors, moved across the ocean surface to follow the northward sea ice retreat. Seagliders measured the upper ocean evolution as a function of distance from the ice edge. "We used gliders to bridge the measurements being made on the ice and in open water," says Lee. "Seagliders sampled from open water, across the MIZ, and under the pack and back again. They collected over 20 sections under the MIZ and pack."

New acoustic navigation capabilities were required for Seagliders to work under the ice, which blocks them from the surface and satellite communications. The solution was acoustic signals sent from ice-tethered navigation beacons and Wave Gliders, each maintaining satellite connectivity at the surface. Because the navigation sources themselves were drifting and gliding on the Beaufort Sea, oceanographer **JASON GOBAT** and engineer **SARAH WEBSTER** designed new algorithms for Seaglider's navigation software. Webster describes the vehicle's 'thought' process saying, "The glider knows the beacons' transmission schedules, then relies on its internal clock to calculate signal travel times, from which it estimates range. Using multiple range measurements, Seaglider can fix its lat/lon position underwater."

The Seaglider sections aimed to follow the ice retreat and stitch together the measurements from platforms in, under, and around the sea ice. On Seaglider recovery cruises in early October, **LUC RAINVILLE** and colleagues conducted 'experiments of opportunity'.

In an Arctic Ocean with larger expanses of open water due to increased sea ice melt during summer, storms have the potential to generate big waves. Analyzing data from satellites and a subsurface mooring in the central Beaufort Sea, **JIM THOMSON** reports that the fetch—the space available for the wind to work on the ocean surface—was so great that 5-m waves were kicked up during a strong September 2012 storm. This represents a dramatic change from past conditions in the central Beaufort and suggests a positive feedback loop—the retreating seasonal ice cover results in larger waves, which, in turn, break up floes and accelerate retreat.

"We sampled the ice edge with an underway CTD round-the-clock, casting every 100 to 200 m and completing hundreds of profiles."

The ocean is more readily heated by solar insolation below low-concentration sea ice, and melting ice freshens the surface layer. From the ice edge out to 15 km into the open ocean, their time series captured these strong temperature and salinity gradients.

Monthly measurements of the ocean, ice, and atmosphere have been taken since 2012 across the Beaufort and Chukchi seas in a collaboration between APL-UW researchers and U.S. Coast Guard Arctic Domain Awareness flights of opportunity. Data from 15 summertime missions that deployed over 100 instruments to date show that the seasonal ice zone — the region between maximum/minimum winter/summer sea ice extent — has a fresher surface layer than in the past due to increased ice melt. The integrated measurements have also identified a strong link between the timing of ice retreat and the wind regime over the Beaufort Sea. These **Seasonal Ice Zone Reconnaissance Survey** measurements are being combined with other remote sensing data and model results to better predict air, sea, and ice conditions in this region of extreme interannual variability.

mizmas

The **Marginal Ice Zone Modeling and Assimilation System** is a robust, high-resolution coupled sea ice–ocean model capable of realistic predictions of sea ice and upper ocean conditions in the Chukchi and Beaufort seas. Led by oceanographer **JINLUN ZHANG**, APL-UW scientists have made breakthrough theoretical discoveries and used observations from the field program and satellite remote sensing to develop MIZMAS. It identifies ice–ocean–atmosphere linkages and interactions that are key to understanding the dynamic and thermodynamic processes that inform accurate predictions of the MIZ seasonal evolution.

Ice floes of varying thickness and size define the MIZ. MIZMAS couples an ice thickness distribution and a newly developed floe size distribution for the first time. The floe size distribution equation accounts for ice motion and freezing, melting along the sidewalls, as well as ice deformation and breakup induced by ocean surface waves. Simulating floe size and ice thickness distributions together will allow additional physics to be incorporated into the next generation of operational forecasts and climate models, such as ice mechanics, surface exchange of heat, mass, and momentum, and wave–ice interactions.

With a successful field season complete, it's time for analysis. Each investigator at the many collaborating institutions holds a piece of the puzzle. Lee sums up by saying, "Now we need to pull all those pieces together to understand what really happened during the year in the Beaufort Sea."

APL-UW polar scientists report that the thinning of arctic sea ice over the past several decades has been dramatic and is showing no sign of slowing. The research team curates the **Unified Sea Ice Thickness Climate Record**, which combines all subsurface, aircraft, and satellite observations of ice thickness since 1975. Their analysis shows a 65% decrease in the September minimum sea ice thickness over that period. Most surprising to them is that the record reveals thinning in the central Arctic Ocean even greater than previous worst-case estimates.

extreme melt: rotting arctic sea ice

Sea ice cover in the Arctic during summer is shrinking and thinning. The melt season is becoming longer and the prevalence of heavily melted floes of "rotten" ice is increasing.

"We are studying the ice as it melts, which sounds simple enough. Most of what's known about sea ice is from floes that have grown over the winter and not yet begun to melt. But the prevalent ice type during summer is heavily melted, fragile, and difficult to work with. Very little is known about it," says lead investigator **KAREN JUNGE**.

photo: Julianne Yip

As a polar microbiologist, Junge is interested in how the sea ice habitat for microorganisms evolves through the melt season. For ice that is structurally sound, much is known about microalgal and bacterial abundance, activities, and diversity. Microorganisms are incorporated into the ice as it forms in the fall and they partition themselves into a web of super salty brine channels that resist freezing. Algae and bacteria produce polymer gel substances that serve cryoprotective and other roles — the organisms micromanage their brine channel habitat.

Junge and her science team want to know how the microbial communities and their gel networks influence sea ice integrity under extreme melt conditions. Summer sea ice evolves as a physical entity, responding to mechanical and thermodynamic forces. It is also habitat to creatures that have an active role in its life cycle. What if the organisms and the polymers they exude actually affect the ice structure?

The requisite multidisciplinary team designed a field experiment based in Barrow, AK, to study first-year sea ice floes through an entire summer melt season in May, June, and July 2015. The sea ice in May has been studied extensively, and the team used standard, accepted methods to take detailed measurements on the floes and to prepare samples for lab analyses — algal and bacterial biomass, abundance, and productivity; polymer gel concentration, composition, and particle size; ice temperature, density, salinity, permeability, optical properties, and microstructure.

the rotten ice team

biological oceanographer **KAREN JUNGE**
physicist **BONNIE LIGHT**
biological oceanographer **MONICA ORELLANA**
geobiologist **CARIE FRANTZ**
micro/molecular biologist **SHELLY CARPENTER**

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Nearly two-dozen, full profile (about 1 m) ice cores were drilled at each study site on the floes and brought back to the Barrow Global Climate Change Research Facility. There, brine was extracted by centrifuge, thin sections were shaved for microscopic analysis in room-size freezer labs, and cores were melted carefully under controlled conditions to probe a multitude of biological and chemical parameters.

When the team returned in June, the floes were visibly different, with contrasting areas of bare ice and surface melt ponds. For the July expedition, the floes were only accessible by boat and the ice had obviously suffered. The surface was rumpled, the texture coarse, and it was riddled with drainage holes.

> *"The ice we found in July was more rotten than my wildest dreams. I've been on sea ice in July and I'd never seen ice just fall apart under my feet the way that ice did."*
>
> – Bonnie Light

For postdoctoral researcher **CARIE FRANTZ**, this was her first field experiment on sea ice. "I had no idea what to expect. Everybody we talked to said we were not going to be able to core and sample sea ice in July. But we cored it and it was intact." Though it was more difficult to find and work with the rotten ice in July, the team conducted their experiments on the floes and prepared samples for lab analyses much as they had in May and June, pulling nearly 1-m-thick cores studded with intense drainage channels out of the summertime ice.

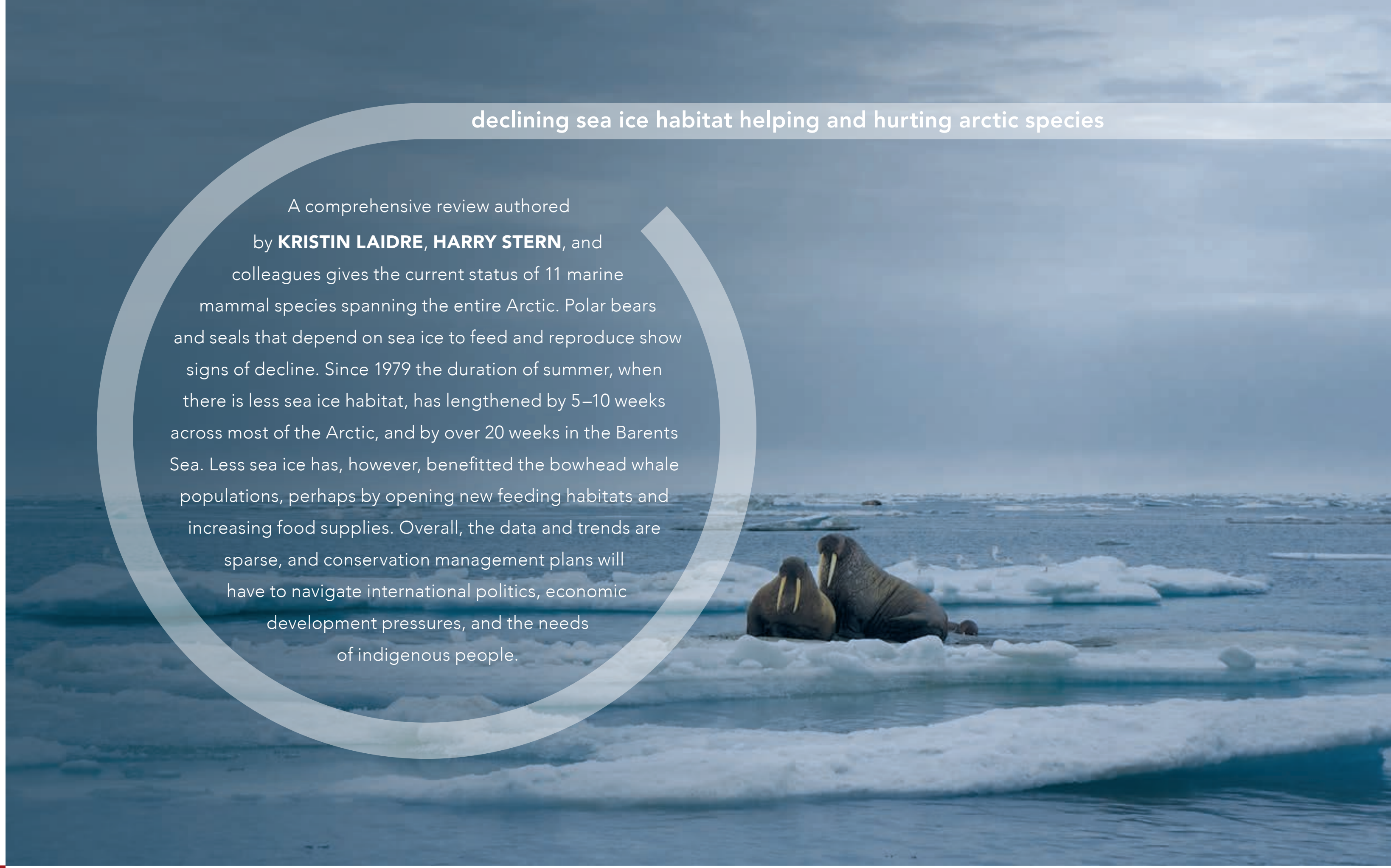
Data from the field and preliminary analysis show core profiles of temperature and salinity that are similar in June and July, while profiles of density show the progression of the melt season very clearly. Optical studies also hint at new insights to rotten sea ice. "The literature states that in general the ice gets more transparent as the spring transitions to summer. And we know that is true for the ice cover as a whole," says **BONNIE LIGHT**. "But my hunch was that the ice becomes *less* transparent as the season progresses. As it warms the inclusions in the ice become larger and they scatter more light. The observations we made bear this out."

photo: Julianne Yip

The team brought back to Seattle 1500 pounds of samples. X-ray tomography will be used to image the internal structure of the rotten ice core sections, flow cytometry will characterize polymer gels in melted samples, and DNA will be extracted for community composition analysis. The team seeks to determine how the ice structure evolved over the melt season, how the cell counts changed, and how the organisms and their exuded polymers were distributed within the brine channels.

Characterizing the physical, biological, and chemical nature of rotting first-year sea ice is the first step toward creating a picture of how the microbial communities interact with and influence their sea ice habitat. Ultimately, the team may tell a new story of how arctic sea ice floes survive the melt season to grow again in the polar night.

photo: Julianne Yip



declining sea ice habitat helping and hurting arctic species

A comprehensive review authored by **KRISTIN LAIDRE**, **HARRY STERN**, and colleagues gives the current status of 11 marine mammal species spanning the entire Arctic. Polar bears and seals that depend on sea ice to feed and reproduce show signs of decline. Since 1979 the duration of summer, when there is less sea ice habitat, has lengthened by 5–10 weeks across most of the Arctic, and by over 20 weeks in the Barents Sea. Less sea ice has, however, benefitted the bowhead whale populations, perhaps by opening new feeding habitats and increasing food supplies. Overall, the data and trends are sparse, and conservation management plans will have to navigate international politics, economic development pressures, and the needs of indigenous people.

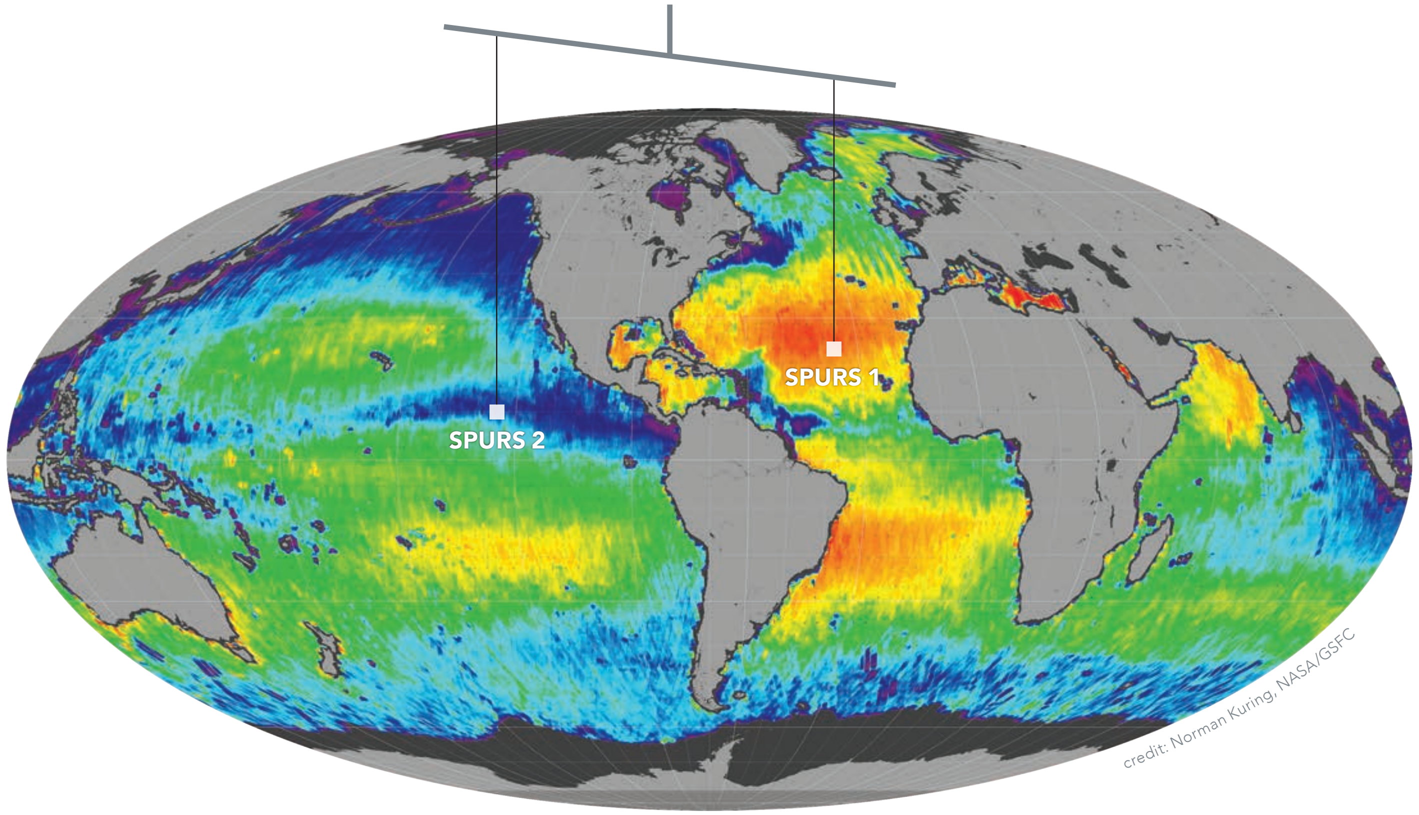
marine mammals in the emerging arctic

non-arctic species more frequent visitors up north

KATE STAFFORD uses hydrophones moored in Bering Strait to identify whale species passing through the gateway to the Arctic. Bowhead and beluga whales, which spend their entire lives in the Arctic, are heard as they migrate from winter habitat in the Bering Sea to summer in the biologically rich Chukchi and Beaufort seas. Recently, the sounds from subarctic species—humpback, fin, and killer whales—have increased. With her long and growing time series of recordings, Stafford hopes to learn if the increasing number of animals traveling through Bering Strait is due to growing populations, or the expansion into habitat made accessible by climate change, and whether the seasonal visitors are competing with arctic species for resources.

salt on the balance

spurs: salinity processes in the upper ocean regional studies



The Earth's hydrological cycle—precipitation, evaporation, freezing, melting, continental runoff, and condensation of water—links land, ocean, and atmosphere. A sign of global climate change is the cycle's intensification: wet regions are becoming wetter and dry regions drier.

Extremes in the cycle impact us as floods and droughts on land, but understanding the variability of the global water cycle means studying the ocean. The ocean provides over 80% of total evaporation and receives about 80% of all rainfall. The balance of evaporation and precipitation between the ocean and atmosphere is marked by salinity—regions of high evaporation and low rainfall are saltier than regions of heavy rainfall and river outflows. Intensification is also evident here: the saltiest regions of the ocean are becoming more saline, while the freshest, fresher.

Sea surface temperature has been measured from space for decades. Recently, with NASA's Aquarius mission and its European analog, the Soil Moisture and Ocean Salinity satellite mission, there is also a global view of sea surface salinity. Satellites sense salinity by exploiting the dependence of the microwave emission of the ocean surface on the conductivity of seawater. Because remotely-sensed sea surface salinity is a new measurement, there is intense interest in understanding its relationship to the underlying processes that determine the global distribution of oceanic salinity.

A multi-institutional, international team of scientists on the **SPURS** expeditions is studying the processes that drive near-surface salinity in both source and sink regions of oceanic salinity and atmospheric fresh water—the salinity maximum region of the North Atlantic (SPURS 1, 2012–2013) and the salinity minimum region of the intertropical convergence zone in the eastern tropical Pacific (SPURS 2, 2016–2017). With a nested web of sensors and sampling strategies—satellites, moorings, intensive shipboard surveys, and autonomous floating and gliding platforms—APL-UW scientists and their collaborators are studying salinity and upper ocean dynamics over many temporal and spatial scales—hours to seasons and centimeters to ocean basins.

an acoustic rain gauge

A **Passive Aquatic Listener** is an acoustic rain gauge developed at APL-UW by oceanographer **JEFF NYSTUEN** that listens for the sound of rain and wind on the sea surface with its broadband, low-noise hydrophone. Ocean ambient sound is recorded and converted to a frequency spectrum, which is then used to detect and quantify rain rate and wind speed. PALs have been incorporated onto Argo floats since 2004; 16 PAL-equipped floats were deployed during SPURS 1 in September 2012. They are low cost, autonomous, persistent, have high temporal and spatial resolution, and transmit data each time the float surfaces.

Physicist **JIE YANG** reports that PAL data from their year-plus drifts in the SPURS 1 region show a correlation of wind speed and rain rate, capture the seasonal and annual precipitation cycle, and give a total annual accumulation. As expected, decreases in surface salinity correlate with intense rain events, but the PAL data also hint at processes and variables other than precipitation and evaporation driving near-surface salinity. Yang notes periods in the data record

"The ocean has its own rain gauge in the form of salinity, and our task in SPURS is to learn how to read it."

– NASA Program Scientist Eric Lindstrom

when salinity remains constant during increasing rain rates and when salinity decreases at times of little rainfall, likely due to lateral advection and vertical mixing in the ocean.

In the precipitation-dominated SPURS 2 region, PALs will be incorporated onto Argo floats, Seagliders, Lagrangian floats, and moorings to make critical measurements of total precipitation input. Measurements from these platforms, plus shipboard rain radar, meteorological, and disdrometer measurements, will be integrated over their range of temporal-spatial scales to draw a comprehensive map of rainfall.

rain puddles on the ocean

In the SPURS 2 region rainfall usually occurs in strong bursts that can last for a few hours, but then not occur again for several days. These events create puddles, or lenses, of relatively fresh and cool water on the surface that can be 10 cm to 10 m thick and about 10 km in extent.

During a three-week intensive observation period that coincides with the rainy season, APL-UW scientists on the R/V *Roger Revelle* will sample rain events to measure the beginning of freshwater input to the ocean and the subsequent formation of surface freshwater lens structures. The life span of a fresh lens is usually less than one day, during which time vertical mixing and lateral surface advection erase the surface freshwater anomaly.

"We need to detect the formation of fresh lenses, track their extent, and measure near-surface turbulence during their life spans."

– Oceanographer Kyla Drushka

Raindrops falling on the sea surface produce turbulence within the upper 10 cm that thickens and deepens the fresh lens structure during the first few minutes to hours. Buoyant lenses create a near-surface stratification that enhances surface currents and reduces turbulent mixing below. These processes are dependent on the rain rate, wind speed, and background near-surface stratification.

What is the relationship between the thermal structure of the sea surface and rain rate during precipitation bursts? How does the fresh lens spread across the upper ocean? An infrared (IR) camera that senses the surface signature of the fresh, cool lenses will give a clear view of lens extent in relation to the rain rate. The camera will be held aloft 100 m above the ocean surface by a large helium balloon launched from and tethered to the stern, giving a bird's-eye view of the lens edge. The IR skin temperature measurements will yield insights into the horizontal structure of the cool surface lenses as they spread, something that has never been measured directly.

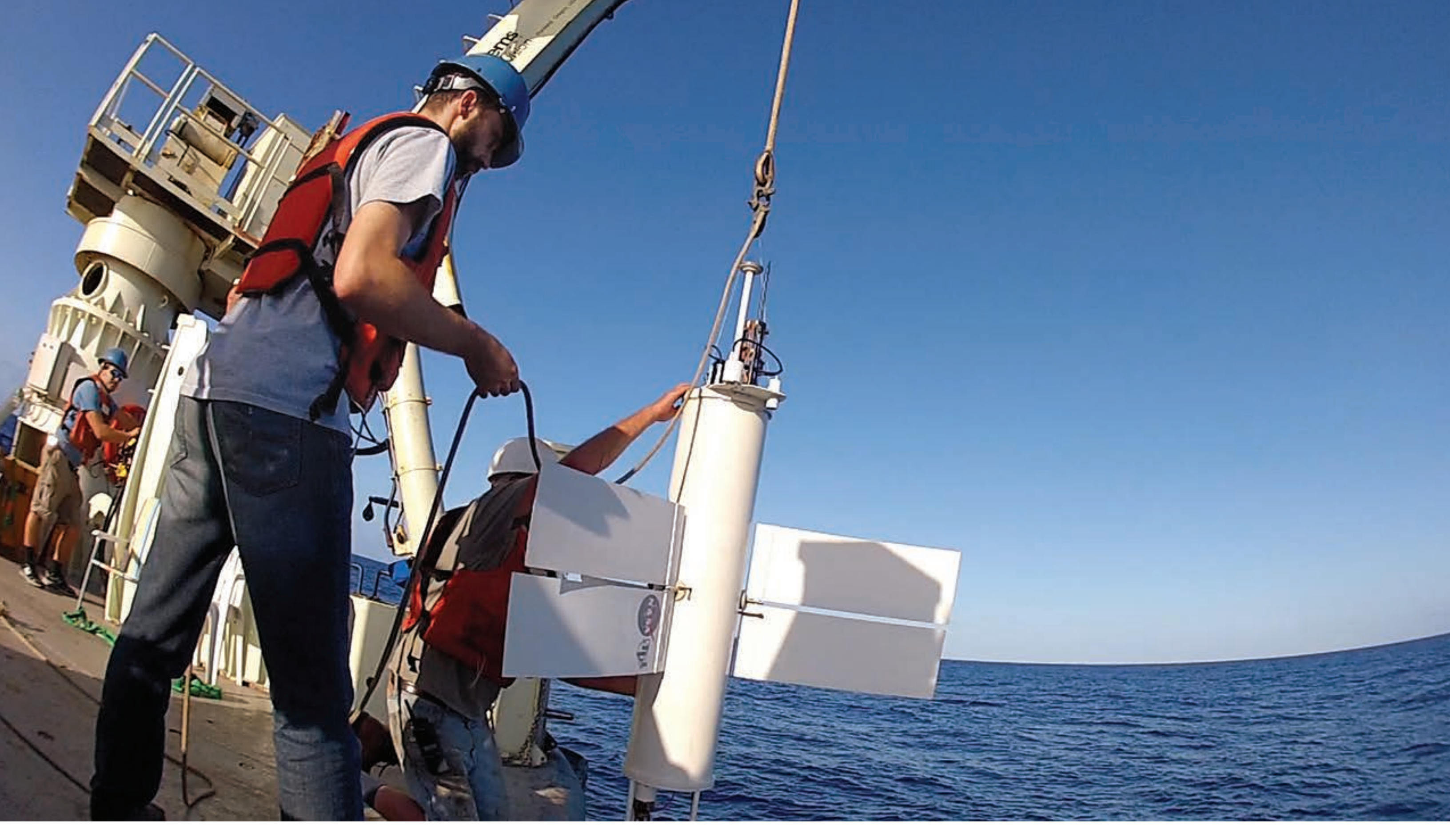
What is the relationship between the surface signatures of turbulence and the stratification caused by fresh lenses and how does it change as the lenses decay? A CO_2 laser aimed at the sea surface will heat a small patch of water that will be tracked by a second, ship-mounted IR camera. The time taken for the heated patch to return to the ambient temperature will provide an estimate of near-surface turbulent mixing. The Surface Salinity Profiler, a surfboard-like platform developed by oceanographers **BILL ASHER** and **ANDY JESSUP**, and engineer **DAN CLARK**, will measure temperature, salinity, and microstructure between a few centimeters and 1 m deep as it is towed through the fresh lenses. SSP surveys before, during, and after rain events will quantify the link between rain and wind forcing at the surface, stratification, and surface mixing within and outside the lenses.

underway salinity profiling

APL-UW engineers will outfit the R/V *Roger Revelle* operated by Scripps Institution of Oceanography with an **Underway Salinity Profiling System** (USPS). During the research cruise portions of SPURS 2 in 2016 and 2017, the system will collect a continuous time series of near-surface salinity and temperature.

When the *Revelle* is in dry dock for overhaul in late 2015, two through-hull ports will be installed by the engineers at depths of 2 and 3 m. When combined with the ship's own thermosalinograph that samples at a depth of 5 m, the data will provide researchers a rich picture of horizontal and vertical salinity and temperature gradients everywhere the *Revelle* sails during SPURS 2 and into the future.

The APL-UW engineers installed a similar system on the R/V *Thomas G. Thompson* operated by the University of Washington five years ago. Studies of *Thompson* USPS data show that temperature and salinity are relatively uniform at 5 m, but vary more at the shallower sampling depths of 2 and 3 m.



a cascade of salinity variance

In parallel with the SPURS 2 intensive shipboard measurements in late summer 2016, a nested web of sensors will be deployed for year-round observations. Lagrangian floats, built by APL-UW in **ERIC D'ASARO**'s lab, will track where and when the freshwater input at the surface is diluted and dispersed vertically to become the eastern Pacific fresh pool. The floats measure turbulence in the ocean mixed layer by following the three-dimensional motion of water parcels through a combination of neutral buoyancy and high drag.

During the SPURS 1 field campaign these floats set records for their longest deployments — nearly 6 months. Oceanographer **ANDREY SHCHERBINA** reports that they observed several types of short-term, small-scale processes in this relatively quiet area of the North Atlantic. During the surface freshening and cooling associated with heavy rainfall events, floats observed the evolution and dissipation of the upper ocean freshwater lenses until the surface anomalies had returned to prior, ambient values. In late winter, corresponding to the maximum density and thickness of the surface mixed layer, floats observed restratification ('slumping') events, where sharp horizontal gradients released energy and slid laterally, moving denser water below lighter. The further breakup and interleaving of these slumped, vertically stratified layers was measured later in the season, giving insight into the processes that yield the smooth, broad salinity maximum characterizing the region.

apl-uw spurs research team

William Asher
Eric D'Asaro
Kyla Drushka
Ramsey Harcourt
Andrew Jessup
Craig Lee
Luc Rainville
Andrey Shcherbina
Jie Yang

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ONR

For SPURS 2, the floats are upgraded to carry upward-looking acoustic Doppler current profilers, making them uniquely capable to measure shear-driven mixing in the surface boundary layer. Floats will be deployed, one at a time, upstream of the SPURS 2 site and will drift through the experiment area on several consecutive, 2-month missions to ensure continuous presence for the entire year-long field campaign.

When the intermittent and short-lived rain puddles are erased from the surface, where does the fresh water go? Where and when is mixing likely to occur? During the rainy season in the ITCZ, wind bursts accelerate the near-surface layer and inertial motions push the energy deeper. On their drift and profile missions under and through the shallow mixed layer, the Lagrangian floats will resolve the intermittent, fast evolution of stratification and shear at the base of the freshwater lenses.

gliding through turbulence

The upper ocean is filled with turbulence. Where is the ocean mixing amid the many fronts and eddies and how does this distribute the near-surface salinity signal in the upper ocean? Since their deployments during SPURS 1, Seagliders now incorporate turbulence microstructure probes, in addition to their conventional suite of sensors (temperature, salinity, dissolved oxygen, and optical backscatter). **CRAIG LEE**, **LUC RAINVILLE**, **JASON GOBAT**, and their development team have integrated microstructure sensors to record the minute fluctuations of temperature associated with the smallest of turbulent eddies hundreds of times per second. Microstructure data are collected on every Seaglider dive and climb without severe drag or endurance penalties. Raw data and profiles of calculated dissipation rates are transmitted to scientists during each surface maneuver and Iridium connection.

Three gliders collected a total of about 2500 profiles of temperature variance dissipation rate in the top 250 m of the ocean during the first 6 months of SPURS 1. They observed the shallow, warm, and salty surface layer deepening, freshening, and cooling during the seasonal fall–winter transition, as well as internal waves, eddies, and high-salinity intrusions at the base of the surface mixed layer. For SPURS 2, three Seagliders on two 6-month missions in the eastern tropical Pacific will measure horizontal gradients and variability of temperature, salinity, turbulence, and shear over a complete annual cycle.

lady amber

The very strong and highly variable currents of the eastern tropical Pacific will present challenges for the autonomous floats and drifters deployed during SPURS 2. Because they will be swept away quickly from the moored assets and 'drivable' robots (Seagliders, Wave Gliders), APL-UW investigators and their SPURS colleagues have chartered the 20-m sailing vessel *Lady Amber*. She will sail bimonthly to the SPURS 2 region to deploy and/or reposition floats and drifters and conduct shipboard sampling near the moorings. The frequent visits and flexibility will be needed to adapt sampling strategies to current conditions, which may be very important in 2016 because an El Niño appears to be developing.

commitment + engagement

regional ocean research fulfills public needs

The past year has been exciting and worrisome for oceanographers. A 'blob' of very warm surface water developed in the northeastern Pacific during 2013–2014 and exerted its influence far and wide, including the inland waters of Puget Sound. Environmental conditions throughout the region in 2015 were unprecedented in the historical record.

APL-UW oceanographers lead efforts to study coastal ocean dynamics, and partner with other research institutions, government agencies, tribes, and industry to monitor conditions in the region and disseminate data-rich information to the public and policy makers. The large anomalies of 2015 motivated scientists to intensify their efforts to gather data over the appropriate spatial and temporal scales to understand the processes that created the 'blob', monitor its effects in real time, forecast impacts, and make the data and their meaning available immediately to the public.

As the anomalous 'blob' water flowed into Puget Sound during late 2014, it was tracked by the ORCA (Oceanic Remote Chemical Analyzer) buoy network—a partnership among APL-UW, the UW College of the Environment and School of Oceanography. Six buoys arrayed throughout Puget Sound carry stationary and profiling sensor packages that measure atmospheric and oceanographic parameters several times every day and transmit them to servers at the University of Washington.

software for science discovery + communication

Easy access to real-time ocean conditions and forecasts for the Pacific Northwest is made possible by the **NANOOS Visualization System** (nvs.nanoos.org). A team of software engineers led by **TROY TANNER** is integral to achieving the NANOOS mission—to provide data and data products from the Pacific Northwest coastal observing system to diverse end users. NVS ingests data streams from a large range of assets and orders them into user-friendly displays.

A recent NVS enhancement, the Climatology App, compares current conditions with a climatological mean derived from long-term satellite and buoy observations. During summer 2015, the app's overlay of climatological sea surface temperature in the northeastern Pacific provided a clear view of the intensity and extent of the 'blob' water anomaly.

NANOOS is the Northwest Association of Networked Ocean Observing Systems; it is an Integrated Ocean Observing System regional association funded by NOAA U.S. IOOS.

"NOAA and others have been measuring pCO_2 and pH at the surface. But maintaining sensors for a time series at depth has not been done locally. We've added them to NEMO and are putting them on ORCA profiling buoys in Puget Sound."

– Oceanographer Jan Newton

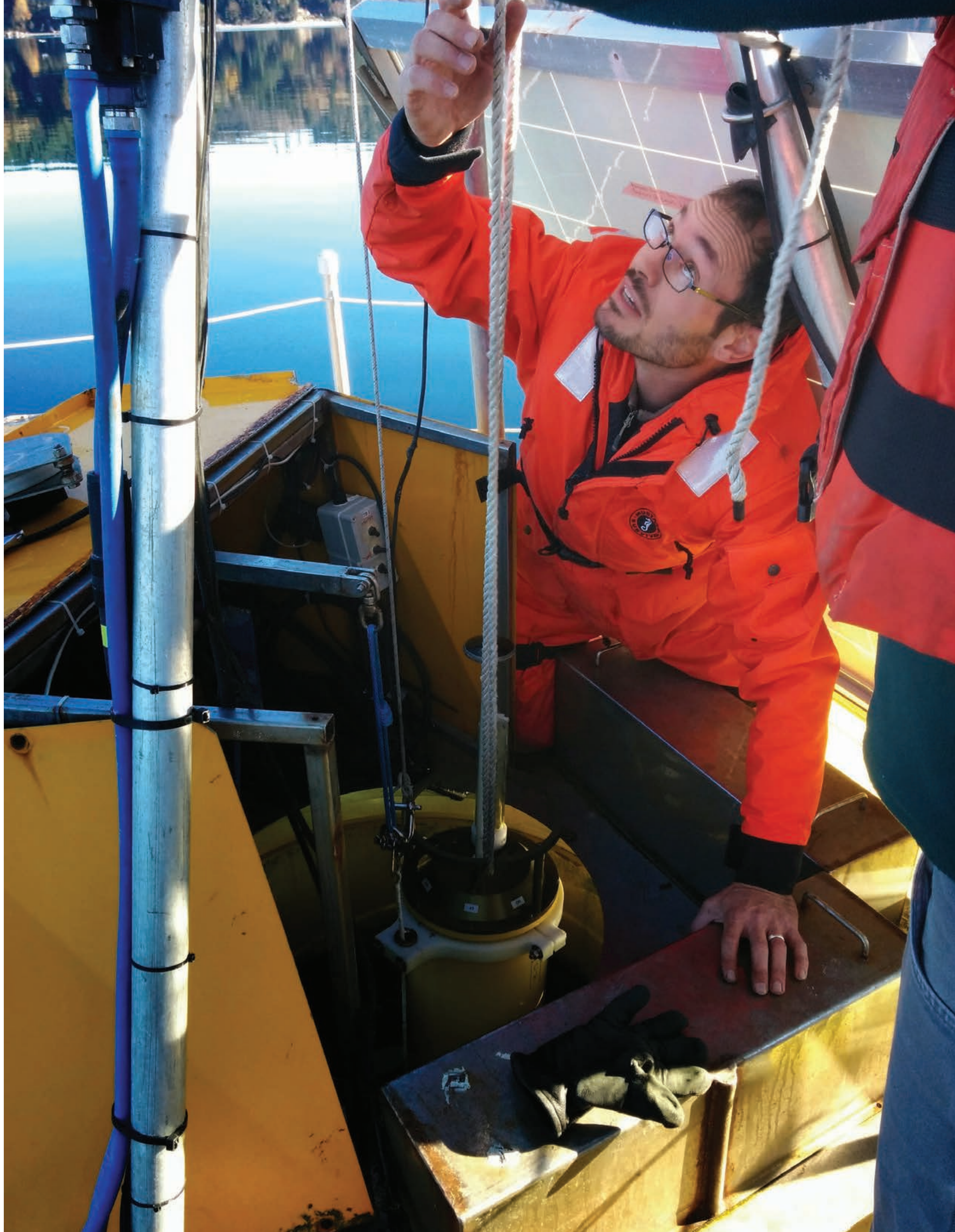
The NANOOS Visualization System (nvs.nanoos.org) serves NEMO, ORCA, and many other pH/pCO_2 sensor data streams, enabling regional ocean acidification monitoring in real time. Pacific Northwest shellfish growers partnered with NANOOS to develop a specialized NVS 'app' that tailors and packages these vital data.

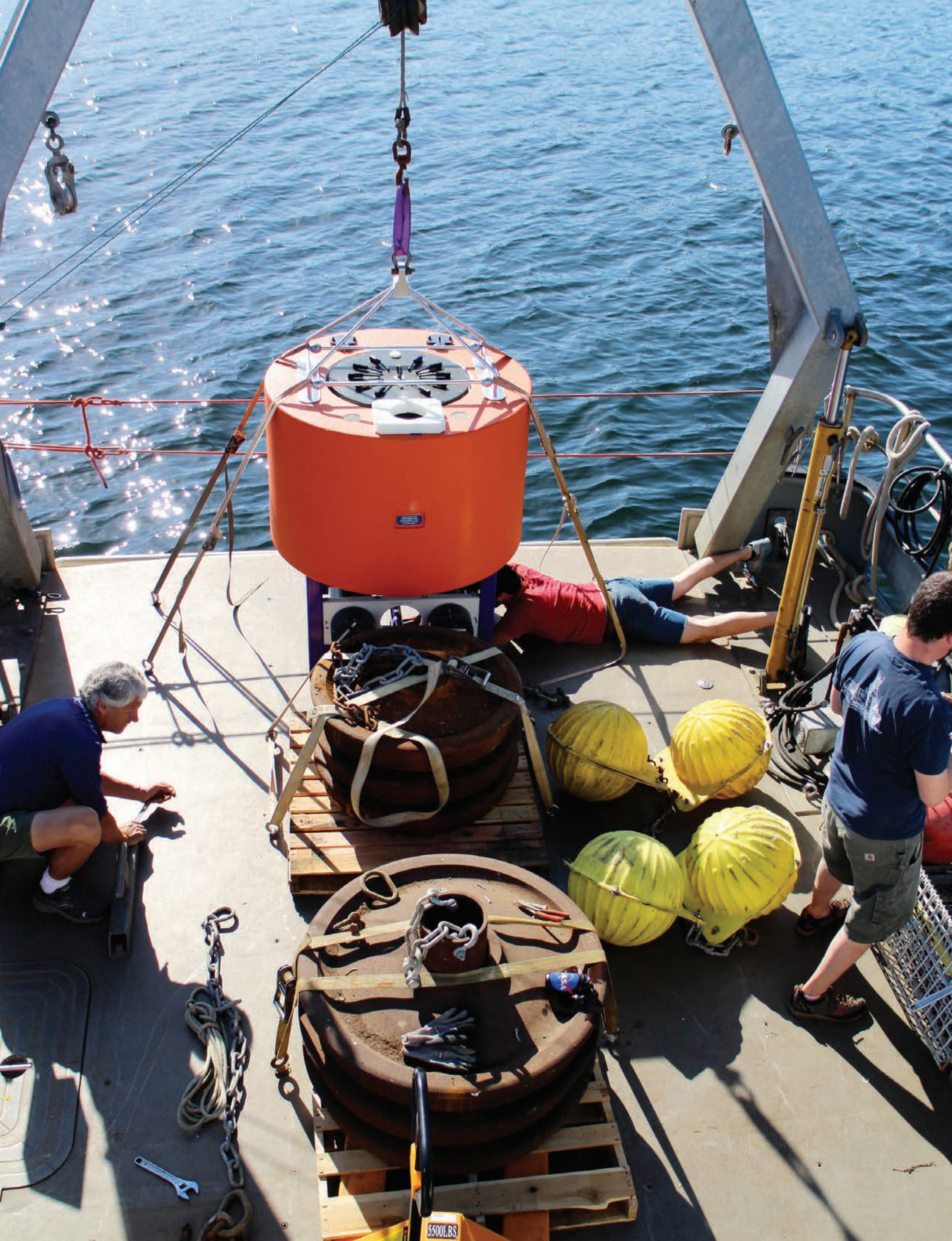
Margaret Barrette, Pacific Coast Shellfish Growers Association Director notes, "The current generation of shellfish farmer is reliant upon data streams and services from NANOOS. Checking the app before seeding a beach or filling a setting tank has become standard practice."

In late 2014, the ORCA program merged with NEMO (Northwest Enhanced Moored Observatory) operations coordinated by **JOHN MICKETT**'s physical oceanography lab at APL-UW. Poised just off La Push, Washington, NEMO is two advanced moorings and a Seaglider transect over the continental shelf that has collected atmospheric and oceanographic data for over five years. In 2015 NEMO observations were augmented by placing pH/CO_2 sensors at depth on the mooring line. Pacific Northwest waters are particularly sensitive to the effects of ocean acidification—the change in ocean chemistry caused by the absorption of CO_2 from the atmosphere. The gas dissolves very efficiently in the comparatively cold and fresh waters of the Pacific Northwest, and natural summer upwelling pushes low pH water to the coastal zone and eventually into the Puget Sound basin.

could seaweed farms mitigate ocean acidification in puget sound?

The Paul G. Allen Foundation is funding a study to find out. APL-UW's regional partners will cultivate seaweed at a demonstration site in Puget Sound. Oceanographers John Mickett and Jan Newton will design the instruments, sensors, and sampling protocols to monitor water chemistry as it passes through the dense kelp beds. Newton, co-director of the Washington Ocean Acidification Center notes that, "Many people have wondered if the uptake of carbon dioxide by seaweed can realistically be used to offset corrosive conditions in a natural setting." The moored instruments will be connected to the NANOOS network, making data available immediately to scientists and the public.





During summer 2015 oxygen readings near the bottom in Hood Canal telemetered by ORCA buoys were near zero, the most extreme conditions measured since the inception of the ORCA program over one decade ago. Typically, oxygen levels recover in fall when the basin is flushed by waters that originate from coastal upwelling and enter through the Strait of Juan de Fuca. The intrusion of very warm, low-density 'blob' water in 2014, however, did not flush inland waters effectively, seeding the extremely low oxygen conditions for the next summer.

APL-UW scientists and their regional partners watched data returns in the late days of summer. Because of the anomalous low density of deep basin waters, the annual, late summer intrusion began earlier than normal—late July instead of September. This conspired with an early fall storm to lift the hypoxic water to the surface, trapping marine life in their last refuge, and causing a significant fish kill event.

Christopher Krembs of the Washington State Department of Ecology summed up the value of the ORCA network saying, "It helps scientists anticipate and sample the events, increasing our understanding of the precise timing of important circulation and mixing processes."

apl-uw orca + nemo research team

Eric Boget
Andrew Cookson
Eric D'Asaro
Al Devol (UW Oceanography)
Hannah Glover
Michael Kenney
Keith Magness
Derek Martin
Nicholas Michel-Hart
John Mickett
Jan Newton
Michael Ohmart
Zoë Parsons
Wendi Ruef (UW Oceanography)
Chris Siani
Rachel Wold

sponsors

NOAA U.S. IOOS
NOAA Ocean Acidification Program
Washington Ocean Acidification Center
M.J. Murdock Charitable Trust
Long Live the Kings

An Environmental Sample Processor will be deployed in a hot spot for harmful algal blooms off the Washington coast. The "laboratory in a can," developed by the Monterey Bay Aquarium and Research Institute, samples the water, processes the genetic material, and identifies microorganisms. It will be added to NEMO, the Northwest Environmental Marine Observatory, sited within the Juan de Fuca eddy.

HABs incubate here and are pushed by winds toward the coast where they inundate shellfish harvest beaches. The ESP data stream will be a vital early detection system. Adding the ESP to NEMO's atmospheric and oceanographic sensing capabilities will enable scientists to study the linkages between HAB outbreaks and environmental conditions as never before.

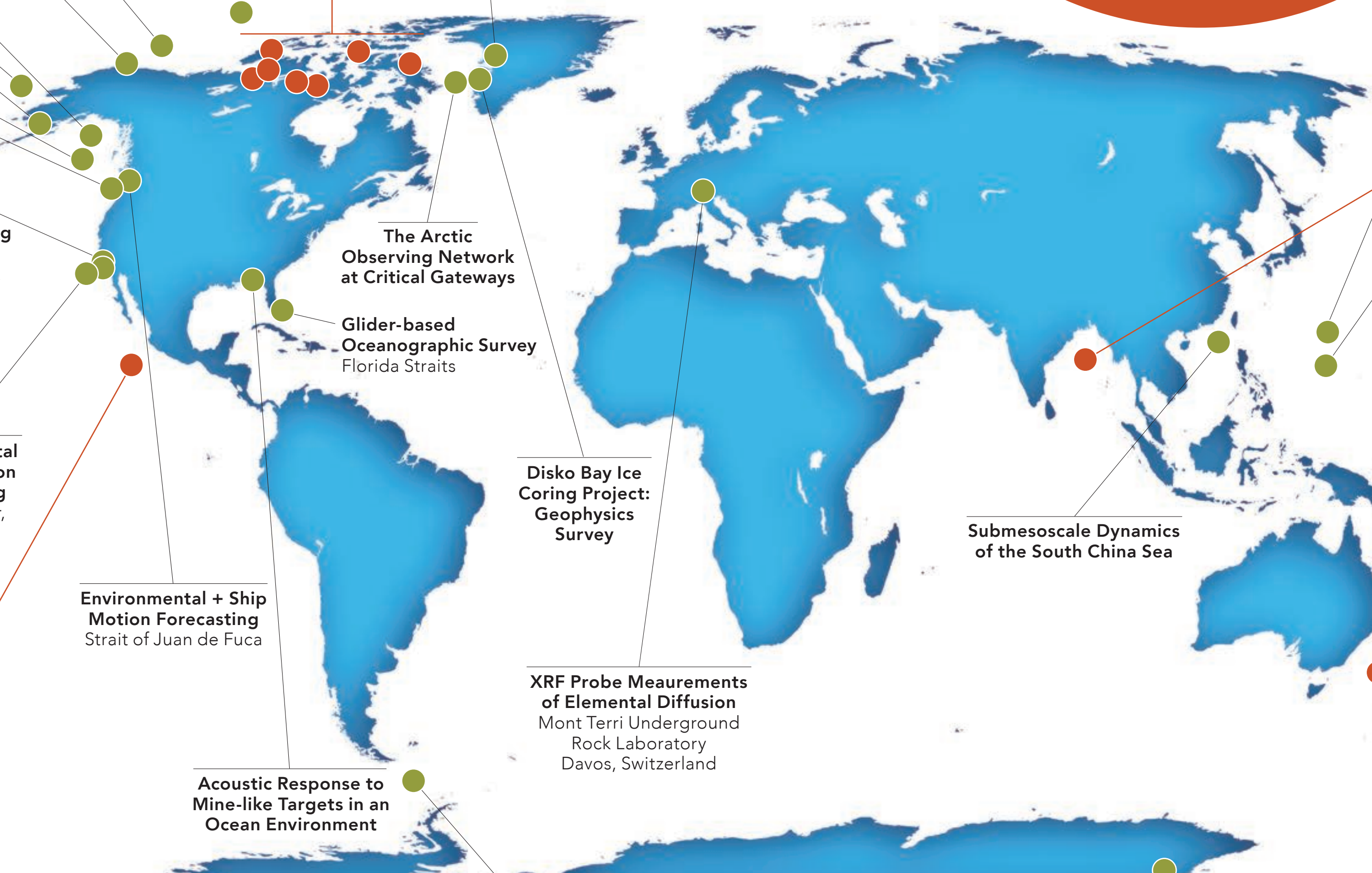
Ferries are now outfitted to study water circulation between the Pacific Ocean and Puget Sound. In a creative and cost-effective partnership with several public agencies, APL-UW scientists and engineers had acoustic Doppler current profilers installed on two passenger/vehicle ferries that cross the channel separating the Strait of Juan de Fuca and Puget Sound. Currents over the full water column are measured during all transits and the data are uploaded wirelessly to land-based computers every time the ferry docks. This long, continuous time series of currents will help scientists and public policy makers understand the Pacific Ocean's influence on Puget Sound water quality—monitoring the flow of potentially low-oxygen, acidic, nutrient-poor, or polluted waters in and out of the sound.

global reach + influence

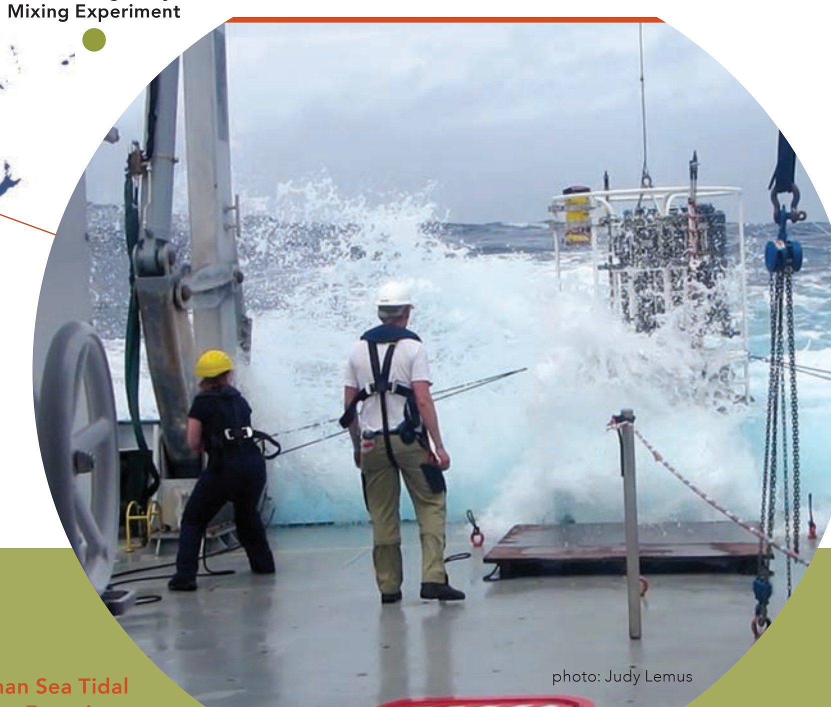
The ability to design, build, stage, and deploy the technology required to pursue ambitious research programs in the field, especially at sea, has distinguished APL-UW since its very beginning. Today, researchers conduct about 50 field experiments across the globe each year. Displayed here is a sample of recent field experiment locations.

Assessing the Impact of Small, Canadian Arctic River Flows (SCARFs) to the Freshwater Budget of the Canadian Archipelago

Air–Sea Interactions in the Northern Indian Ocean



Autonomous Lagrangian Floats for Oxygen Minimum Zone Biogeochemistry



Tasman Sea Tidal Dissipation Experiment

plugged into the deep ocean

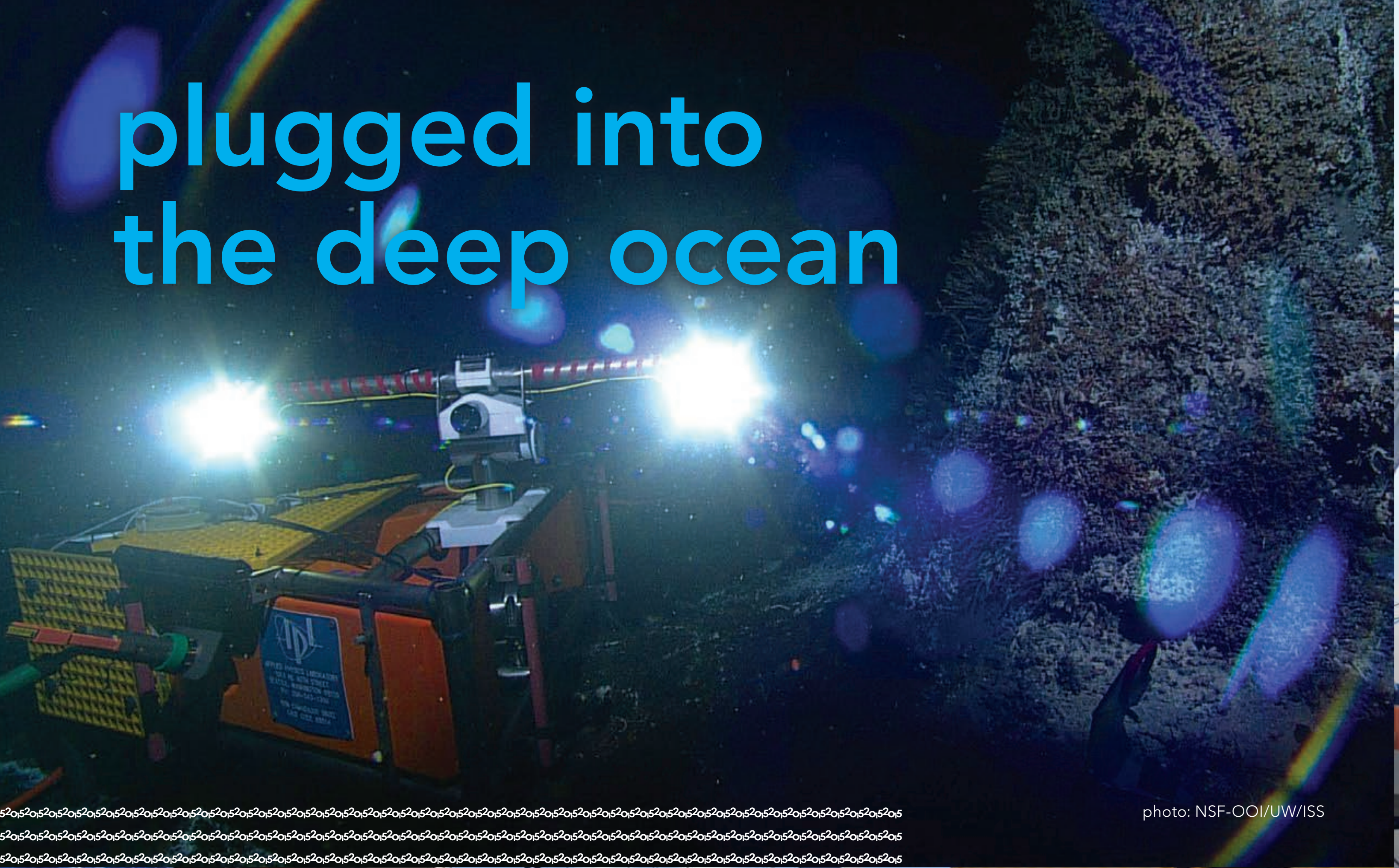


photo: NSF-OOI/UW/ISS

photo: Mitch Elend, UW

Installation of the world's largest undersea observatory is complete and the first annual cabled array operations and maintenance cruise was a success in summer 2015. The National Science Foundation Ocean Observatories Initiative Cabled Array is a power and communications network that links together 130 scientific instruments and stretches hundreds of miles off the Pacific Northwest coast.

APL-UW engineering expertise has been a big part of making this vision a reality. Now and for decades to come over the observatory's life span, there is a continuous, live, and online human presence extending across the ocean floor and through the entire water column. Observations from the NSF/OOI cabled array will inspire and inform scientific inquiries never before possible.

photo: Deb Kelley, UW

science + technology for the next navy

At-sea ESMF trial with the USNS *Montford Point* and USNS *Dahl* 10 miles east of Oahu in spring 2015

watching waves to predict motions on the ocean

An APL-UW research collaboration with Applied Physical Sciences Corp. has developed a radar system to detect waves when U.S. Navy operations require stability on the ocean surface. Wind-driven waves and swell that pitch, heave, and roll vessels are an ever-present risk during ship-to-ship transfers of personnel, equipment, and cargo on the open ocean. Imagine a ramp connecting two ships, with people and vehicles moving across, or a crane lifting and placing cargo containers from one deck to another. The Navy's envisioned solution is **Environmental and Ship Motion Forecasting**, where the evolving wave field is measured at high levels of accuracy and the ship's motion in response to the waves is predicted. ESMF could extend the operational environment of ship-to-ship transfers to greater sea states as well as predict unsafe conditions with sufficient time to revise or call off operations.

GORDON FARQUHARSON and **BILL PLANT** supplied radar and wave sensing expertise, which APS integrated into an ESMF system made up of several components — a custom radar that measures wave properties, a wave retrieval system that reconstructs the wave field as it approaches the ship, a ship motion sensor, and a ship motion model that integrates the wave retrieval and motion sensor inputs to generate a forecast of the ship's response to the wave field in the future.

Farquharson and Plant first addressed the radar remote sensing problem by describing the fundamental physics of electromagnetic signal scattering from the sea surface. It is a technical hurdle to infer ocean wave properties from scattered radar signals. For example, the intensity of the scattered signal is related to the wave slope, but not by a scaling factor, and no empirical model captures the complexity under all sea states. The Doppler shift induced by waves is related to wave orbital velocity, but the relationship is complicated by wave breaking. And though there are models that capture many features of electromagnetic scattering from the sea surface, they are computationally intensive and could not be used in a wave retrieval and forecast system that must run in real time.

In light of the physics and signal processing challenges, the team designed a custom radar suited to the problem. To detect landforms, vessels, and other objects, marine navigation radars use horizontal polarization to minimize backscatter from the sea surface. But here, a vertical radar polarization scheme is implemented to intensify scattering from the non-breaking waves. Coherent transmission provides more power, greater sensitivity, and the ability to calculate the Doppler shift induced on the electromagnetic signal by the waves. And slowing the rotation speed while using multiple antennas allows enough time to make a good Doppler measurement while preserving the revisit time of the radar at points across the ocean surface.

Custom mast-mounted antennas and electronics were constructed according to specifications generated by the APL-UW/APS team. A deck-top unit, housing data acquisition and networking equipment, radar electronics, and a GPS receiver, complete the radar component of the ESMF system.

During an at-sea trial on the R/V *Melville*, the team had startling evidence of the system's potential. During a period when the typical ship motion was an average 5° roll, the ESMF system forecast a roll of 11° happening in 45 seconds. There was little, if any, visual warning of the event, but it did occur at the forecast time when a convergence of several waves near the vessel produced a 12° roll.

apl-uw esmf research team

Gordon Farquharson
John Mower
William Plant

During ESMF sea trials, other wave sensing platforms were deployed on the sea surface. Comparing their data records to the wave retrieval estimations helps to refine the model simulation.

The flexible system architecture implemented by APS makes a seamless transition from single- to multiple-radar ship motion prediction by networking through RF communications the data streams from multiple sensors on one or many ships and platforms. For example, when two ships draw near in a ship-to-ship transfer operation, the first is likely to partially or completely block a second ship's view of approaching waves, compromising its motion prediction. In this scenario radar data from the first is used to drive the wave field estimation and motion prediction by both ships.

ESMF is a critical component of the Navy's sea-basing strategy—to create ports at sea that enable rapid responses to emerging security or humanitarian crises without shore-based support. It is a Future Naval Capability effort supported by the Office of Naval Research Sea Warfare and Weapons Department.

tactical oceanography

To detect and identify dangers in shallow, coastal waters, U.S. Navy sonar operators must deal with the effects of reverberation. Echos from bottom and surface boundaries, sensitive to influences from a myriad of environmental features and oceanic processes, contribute to acoustic clutter.

Acoustics researchers at APL-UW have devoted considerable effort to study mid-frequency reverberation in shallow water. The combination of acoustic data, detailed environmental characterization, and precise measurement geometries from the recent TREX13 experiments make these data uniquely suited to the goal of testing standard Navy codes. With small business technology transfer funding, APL-UW acousticians are working with algorithm developers to sharpen mid-frequency sonar performance in cluttered, shallow water environments.

commanding a robotic fleet

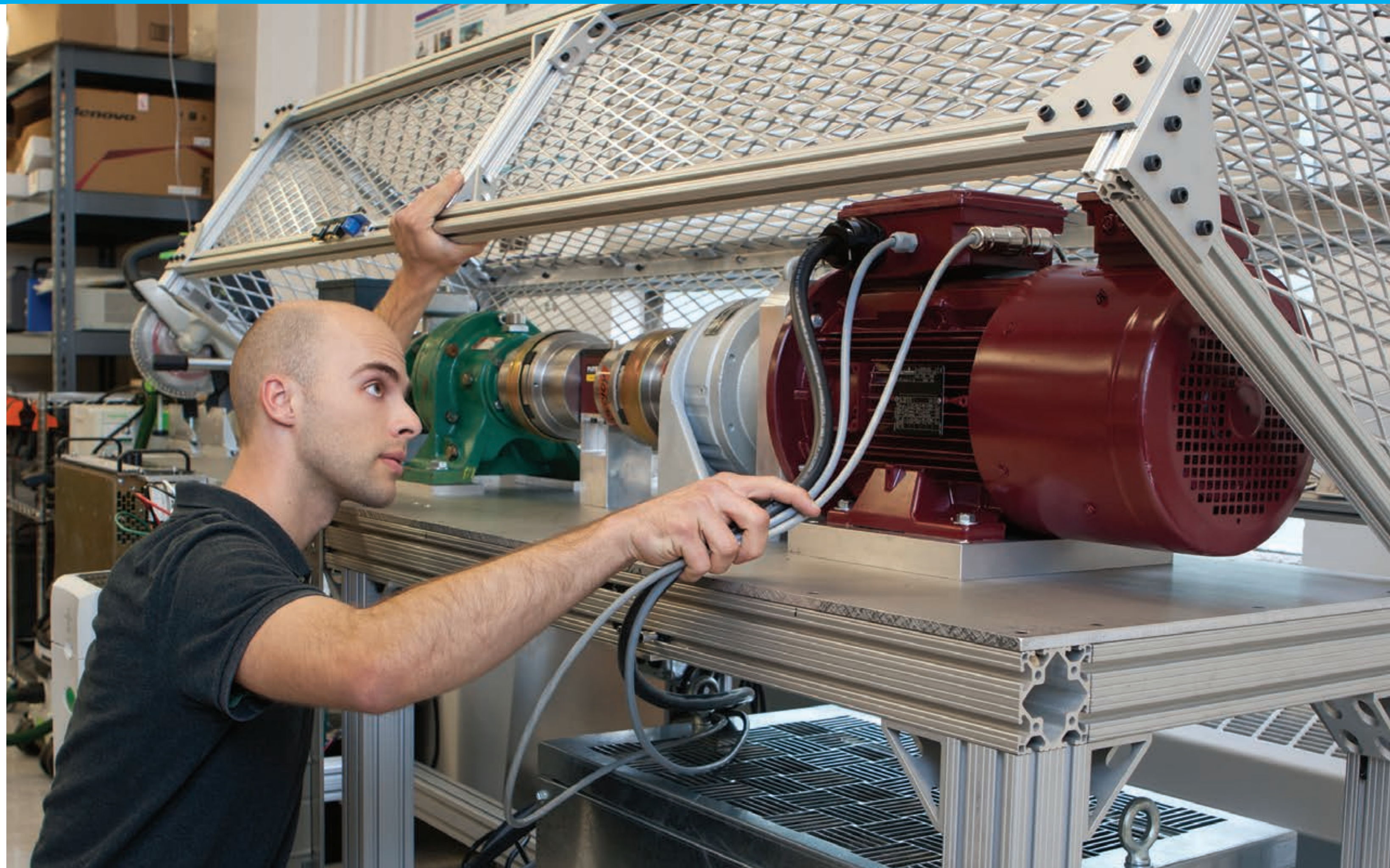
Software used every day by U.S. Navy personnel to operate a fleet of robotic systems was developed at APL-UW. Expertise in software engineering, graphical user interface design, human–computer interaction, and ocean glider technologies were used to create the **Glider, Monitoring, Piloting, and Communications** system.

Robotic ocean-going platforms—gliders and floats—have transformed the U.S. Navy's collection of relevant physical oceanographic data used to maintain strategic and tactical advantages. NAVOCEANO Glider Operations Center pilots drive multiple types of vehicles simultaneously with GLMPC. Instructions input through the graphical user interface are translated into commands expected by each vehicle type. And to help pilots achieve complex mission requirements, GLMPC integrates the location of these platforms, their sensor observations, and forecast model data.

hydrokinetic energy conversion

The U.S. Navy has set a goal of obtaining one-half of its energy from renewable sources by 2020. APL-UW ocean engineers are working to meet that challenge with marine renewable energy technologies. Engineers are studying turbines and wave energy converters that have power takeoff units designed to couple hydrodynamic forces with generators to produce electricity. A primary challenge is to tune the devices to generate ample power in areas of low resource levels, that is, weak currents and small waves.

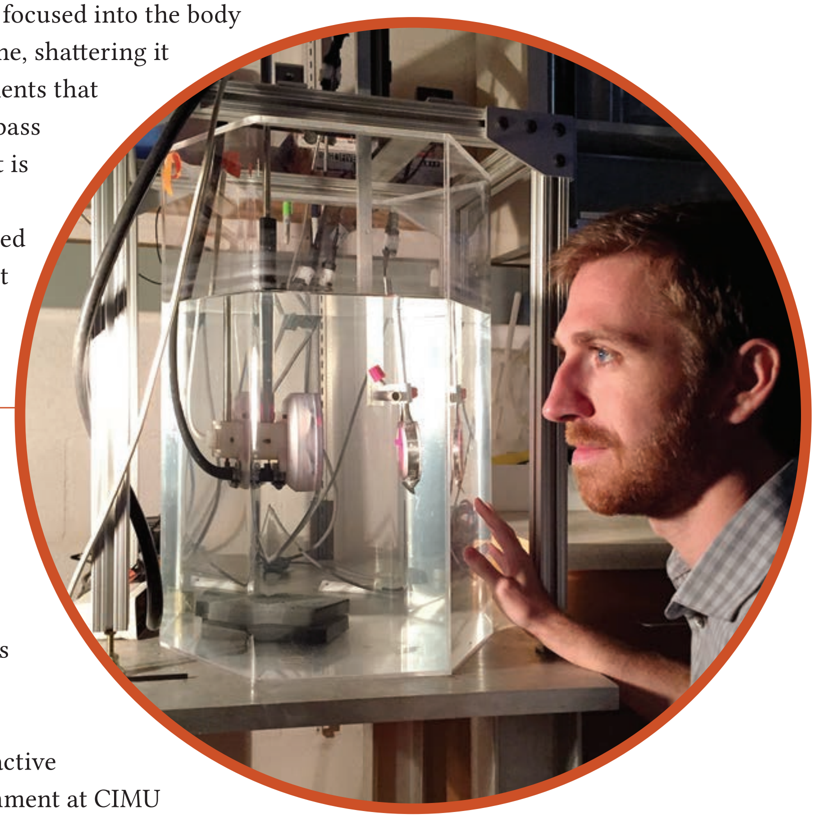
With collaborators in the UW College of Engineering and the Northwest National Marine Renewable Energy Center, the engineering team is now transitioning numerical and laboratory results to a series of functional field-scale prototypes with load handling, power conditioning, and data acquisition systems that will be tested on APL-UW's R/V *Henderson* in Puget Sound.



sound waves crumble stones

Researchers at the APL-UW Center for Industrial and Medical Ultrasound and the UW Department of Urology are working to develop a safe, noninvasive way to fragment kidney stones so they may pass naturally.

Current state-of-the-art for kidney stone treatment is extracorporeal shock wave lithotripsy—a procedure where acoustic shock waves are focused into the body and onto the stone, shattering it into small fragments that the patient will pass spontaneously. It is noninvasive and therefore preferred by patients, but it is unsuccessful about 40% of the time and large residual stone fragments sometimes remain that require repeat treatments or invasive methods of extraction.



ADAM MAXWELL's vision is to use ultrasound pulses rather than shock waves to break kidney stones.

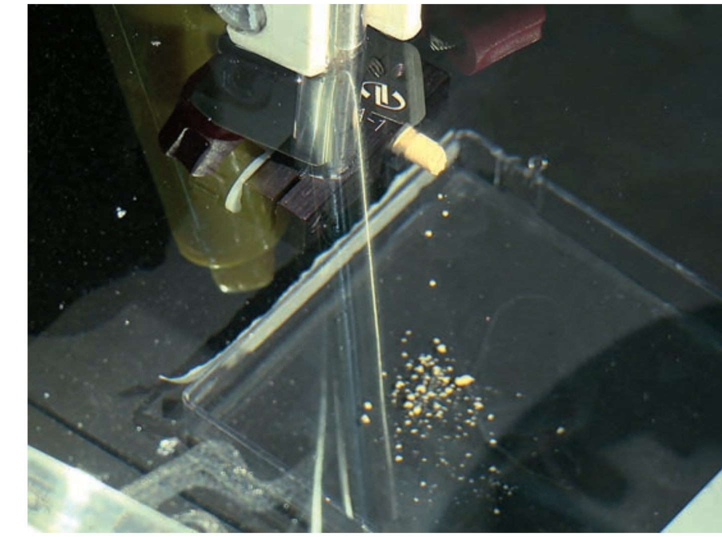
A decades-long active research environment at CIMU to understand the physics of how shock waves fracture stones has identified two important mechanisms. Elastic shear waves create tension that causes a localized fracture point on the side of the stone away from the acoustic source. Cavitation—bubble generation and implosion caused by the acoustic pressure fluctuations—at the stone surface also initiates fracturing, but a proliferation of cavitation bubble clouds caused by delivering shocks at too great a rate decreases effectiveness and can damage tissue.

apl-uw bwl research team

Michael Bailey
Bryan Cunitz
Barbrina Dunmire
Madeline Hubbard
Christopher Hunter
Vera Khokhlova
Wayne Kreider
Adam Maxwell
Yak-Nam Wang

sponsors

National Institute of Diabetes and Digestive and Kidney Diseases
National Space Biomedical Research Institute



Optimized lithotripsy treatments are those that excite shear waves within the stone and minimize cavitation clouds. Maxwell's team calls their recent invention **burst wave lithotripsy** because it applies sinusoidal ultrasound bursts at much lower pressure amplitudes compared to shock wave lithotripsy. This is 'buzzing' instead of 'banging' against a kidney stone, where consecutive acoustic cycles concentrate energy within the stone, causing stresses and fractures through resonances that eventually fragment the stone at relatively low peak pressures. BWL produces evenly spaced fractures along the stone surface, resulting in fragments that chip away from the stone's face nearest the transducer until it's disintegrated.

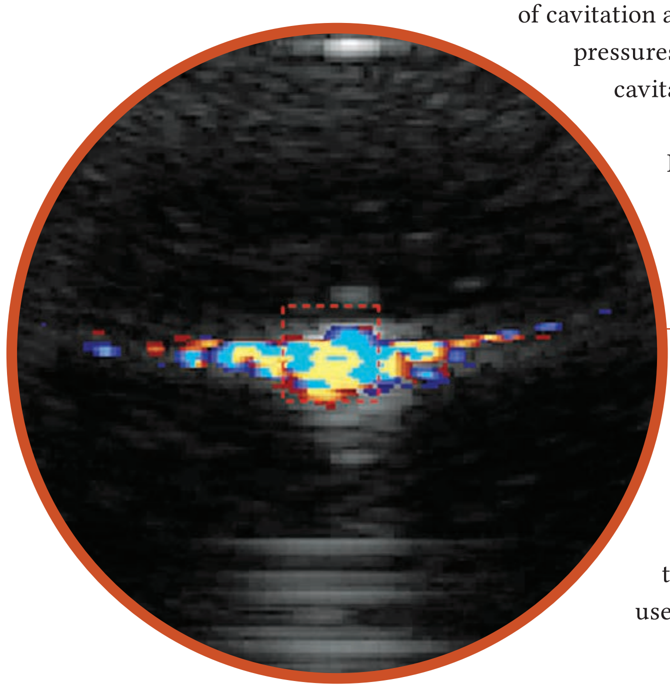
Undergraduate researcher **MADDIE HUBBARD** exposed real kidney stones and model stones cast in the lab to ultrasound. She found that treatment can erode stones of various size, shape, and hardness into uniformly sized fragments, which is providing useful data to guide models of BWL treatment. Maxwell notes, "The softest stones crumble in a few seconds, while the hardest stones take 10 to 20 minutes. This is an improvement over a shock wave lithotripter, where treatment is usually about 30 minutes and can be as long as one hour."

The discovery that may be most important clinically is that BWL breaks stones into uniform fragments and the system can be 'tuned' to optimize treatment. When operated at higher acoustic frequencies, BWL erodes the stones into smaller fragments that are more likely to pass spontaneously through the urinary tract.

is it safe?

Because BWL operates at relatively low acoustic pressures, it is expected that the risk of kidney tissue damage during treatment is reduced. Indeed, exposures have been identified that cause no thermal or mechanical injury, while still producing stone disintegration.

CHRIS HUNTER, another undergraduate student researcher in the lab, is running a series of experiments on a material that mimics kidney tissue to find a minimum pressure where no cavitation is observed in the 'tissue' or on a kidney stone nestled against it. Using high-speed photography to capture the initiation of cavitation activity, his results will help determine what pressures can be applied to fragment stones without causing cavitation in tissue.



Real-time monitoring with ultrasound imaging is used to target the focused ultrasound to the stone. When ensonified with imaging ultrasound, the hard, faceted surface of the kidney stone 'twinkles' on a color Doppler display. Student researcher **ANNIE ZWASCHKA**'s lab experiments are demonstrating how the feedback on the ultrasound imager changes during treatment. The total surface area excited by ultrasound increases as fragments crumble away from the stone, increasing the brightness of the 'twinkling'. The team hopes this effect may be used to determine a therapeutic endpoint.

idea >>> impact

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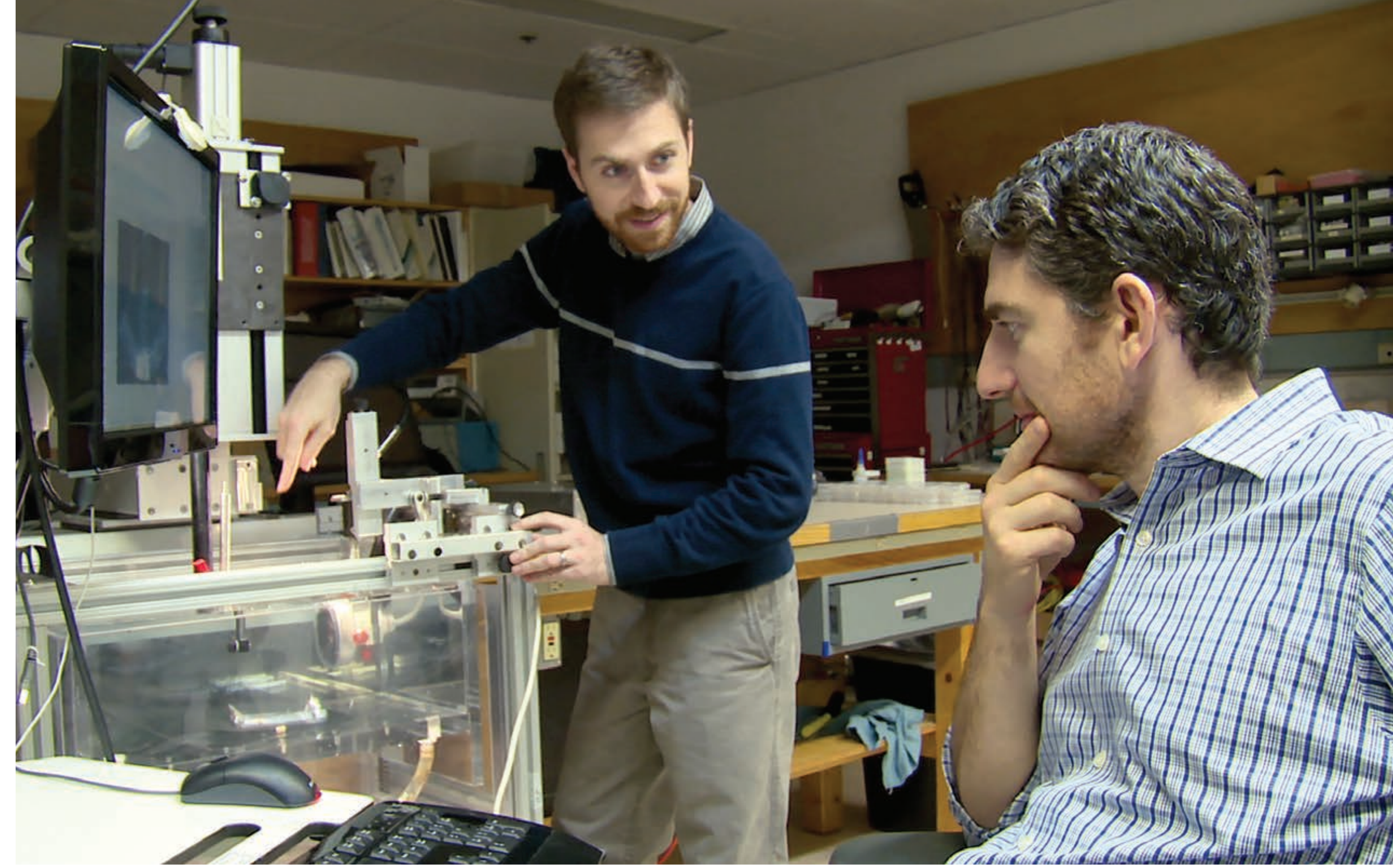
SONOMOTION, the company spun off from innovations to move kidney stones with ultrasound, has licensed a substantial portfolio of intellectual property from APL-UW burst wave lithotripsy research. The company's goal is to market an all-in-one, noninvasive kidney stone treatment solution. An ultrasonic imaging, breaking, and repositioning system that eliminates the need for ionizing radiation and general anesthesia represents a major advance in kidney stone disease treatment.



device development for medical research

A CIMU team is developing an **acoustic caliper to assess the fat content in donor livers** being considered for transplantation. Many potential donor organs are rejected unduly based on subjective metrics such as a surgeon's visual assessment. Acoustic calipers may provide rapid, quantitative evaluation of fat content. The device is two ultrasound transducers mounted to a frame, with one transducer delivering an ultrasound pulse and the second sensing the pulse that has traveled through the tissue.

The team has succeeded in discerning the type — large or small lipid droplets — of fat in tissue phantoms and is working to optimize caliper performance and begin tests on liver tissue. This device, with potential clinical application, grew from basic research to develop a method to characterize sound speed, attenuation, and nonlinearity of ultrasound through tissues. These properties are relevant to any therapeutic ultrasound device in which treatment protocols must be designed to deliver appropriate doses of ultrasound to targeted tissue.

A simple ultrasound device holds promise to speed the **search for disease biomarkers and improve drug discovery** methods. Cancer, heart, kidney, and neurodegenerative diseases are caused by the abnormal expression of genes. Researchers, clinical labs, and pharmaceutical companies use ChIP (chromatin immunoprecipitation) assays to search for disease related genes that have been altered by interaction with proteins. Small samples of chromatin or DNA must be sheared into random but tight size distributions, without contamination or sample degradation. Ultrasound is the standard method.

The device, developed by CIMU researchers and collaborators in the UW Department of Medicine, is fully automated and has no moving parts. Cells are grown, harvested, and sheared in one 96-well plate with a transducer element dedicated to each well. With all elements operating in parallel, and without the need to transfer samples, it ensures sample integrity and achieves reproducible results and high throughput.

innovation imperative

Much of APL-UW's success is based on its vertical integration of fundamental science, applied research, and technology development. Transitions of technology to the fleet and to industry are tangible proof. With close bonds to the University of Washington—a research colossus—the Laboratory's scientists, engineers, and students are making significant contributions to a burgeoning regional innovation ecosystem.

The Laboratory's mission to advance discovery and invention, and to educate future creative problem solvers aligns with the University's initiative to promote an innovation mindset across the institution—training technical expertise, growing entrepreneurial spirit, and inspiring engagement with societal challenges.

In 2014 the UW was named the 'emerging incubator of the year' and launched an all-time record 18 start-up companies—besting the previous year's 17. In the most recent fiscal year APL-UW innovations resulted in 20 invention disclosures to the UW, 41 patent applications, 6 patents granted, 22 commercialization licenses, and the spinoff of five new companies.

each of these companies began as a researcher's idea

BluHaptics

The technology spun off to create **BLUHAPTICS** began with an idea that it should be as easy and intuitive to guide a robot's manipulation tasks on the deep seafloor as it is to gesture with your own hands. The research team combined **telerobotics**—controlling robots from a distance—and **haptics**—tactile feedback technology that gives touch sensations through forces and vibrations—to create control systems for underwater remotely operated vehicles. Research in both areas originated in the UW Bio-robotics Laboratory, where they were being used to improve robotic surgeries. Ocean engineering expertise at APL-UW transitioned the control and feedback algorithms to a sub-sea manipulation interface that allows ROV pilots to guide the robot's movement with a joystick, which translates force feedbacks from sonar, video, and laser sensor inputs.

BluHaptics technology is being well-received by the offshore oil and gas industry at trade demonstrations. The software-based solution promises greater precision, efficiency, and safety for ROV operations.

SonoMotion

A research team in the Center for Industrial and Medical Ultrasound invented a new way to move kidney stones inside the body with ultrasound. The technique facilitates the passage of small stones or the fragments left behind after shock wave, stone-breaking treatments, and helps to dislodge large, obstructing stones that often result in emergency surgery.

Now, the spinoff company **SONOMOTION** is developing a commercial-ready system with the aim of garnering regulatory approvals for the system and marketing the product to hospitals and clinics around the world. SonoMotion has licensed the stone propulsion technology with the UW and has raised over $2M.

Only five years ago the researchers were inspired by their discovery that stones could be moved with ultrasound. Their work has been quick and inexpensive, resulting in the successful demonstration of a therapeutic device in people.

MARQMETRIX

The optical, light-sensing, measurement technologies commercialized by **MARQMETRIX** help manufacturers across a broad spectrum of industries assure quality and reduce errors. Research at APL-UW developed a Raman spectroscopy instrument and immersion probe capable of determining qualitative and quantitative molecular information from solids, liquids, and gases, either static or flowing.

MarqMetrix now has an exclusive license agreement with the UW for the Raman BallProbe™. This hand-held probe ends in a spherical sapphire tip that emits laser light. Placed on or in any material and connected to a spectrometer, it gives near-real time feedback about the sample's chemical properties and molecular structure.

the Collaboratory at APL-UW

THE COLLABORATORY AT APL-UW, established in 2014, is a new venture for the Laboratory and its industry partners to advance technology development and have a rapid impact on commercial enterprise. The Collaboratory fosters research and engineering partnerships between academia and industry by bringing together in a common workspace a critical mass of expertise, infrastructure, and resources in marine technology.

The Collaboratory partnership with **OCEANGATE** has matured the concept of contract engineering between APL-UW and private industry. Laboratory engineers committed thousands of hours of expertise toward *Cyclops*, the company's carbon-fiber hulled submersible that will take a crew of five to a depth of nearly two miles.

photo: Mary Levin

"We couldn't have done it without the partnership. The Applied Physics Laboratory has been our primary engineering partner."

– Stockton Rush, CEO and Founder
OceanGate, Inc.

accolades

university of washington distinguished staff award

BRYAN CUNITZ, **BARBRINA DUNMIRE**, **MARLA PAUN** (posthumously), **FRANK 'RUSTY' STARR**, and **YAK-NAM WANG** were recognized for their invention of a revolutionary treatment that uses ultrasound to move kidney stones painlessly inside the body to help them pass naturally. They are the first research team at the UW to invent a device, be granted an investigational device exemption from the U.S. Food and Drug Administration, and pursue a clinical trial of a medical therapeutic device.

"Their accomplishment is truly unique, medically and financially valuable, and laudable."

– Physicist Lawrence Crum
Founder, Center for Industrial and Medical Ultrasound

project of the year award

SERDP (Strategic Environmental Research and Development Program), the DoD's environmental science and technology program, recognized **STEVE KARGL** and co-investigators **KEVIN WILLIAMS** and **AUBREY ESPAÑA** for their milestone experiments showing that low-frequency sonar can be used to detect and classify underwater munitions in real-world, open water settings.

the technical cooperation program team award

DAVID KROUT and **BOB MIYAMOTO** were presented a team award by TTCP, the defense and science organization that promotes collaborative exchange and joint trials among Australia, Canada, New Zealand, the United Kingdom, and the U.S. To improve antisubmarine warfare operations, their team developed and employed a cross-evaluation method based on a common multi-layer simulation scenario set. Their results set benchmarks of all nations' models and developed a method to calculate residual risk for multistatic operations.

fellow, national academy of sciences

ERIC D'ASARO was elected to the National Academy of Sciences. D'Asaro's distinguished career is marked by studies of ocean turbulence and mixing in environments ranging from coastal currents to the deep sea and beneath hurricanes. For the past 20 years he has developed a unique type of underwater float and used the technology to measure ocean turbulence and its effect on biological activity.

university of washington 2015 innovation award

A cross-disciplinary team including **PAYMAN ARABSHAHI** and three more professors is creating a web-based program to provide mentoring and a support network for innovation readiness to all UW students. The goal is to help students acquire entrepreneurial thinking skills and improve their problem-solving abilities no matter their major.

"These are some of the most creative thinkers in our midst and are at the heart of the UW's innovation ecosystem."

– UW President Ana Mari Cauce

fellow, american geophysical union

Glaciologist **IAN JOUGHIN** has been elected fellow for his pioneering methods to measure the speed and dynamics of the ice sheets in Greenland and Antarctica. Recent work has clocked unprecedented glacier speeds in Greenland and predicted the slow, inevitable collapse of the West Antarctic ice sheet. His work has increased understanding of the ice sheets' mass balance and forecast their contributions to global sea level rise.

photo: Chris Linder

special achievement award

BOB MIYAMOTO was honored by the Undersea Warfare Division of the National Defense Industrial Association in 2015. He is recognized for his outstanding contributions to data-driven analyses and environmental-adaptive algorithm development, which have resulted in improved performance prediction, mission planning, and performance of undersea acoustic detection systems.

university of washington presidential innovation fellow

LEE THOMPSON has been named a fellow of the prestigious group by UW President Cauce based on his long record of entrepreneurial thinking and impactful innovations. With sonar technologies developed and spun off from APL-UW research, he co-founded BlueView Technologies, Inc., and led the company's international growth for eight years until its acquisition by Teledyne Technologies, Inc. Thompson returned to APL-UW in early 2014 to pursue his passion for technology development. As a Presidential Innovation Fellow, his expertise is made available widely across the vibrant translational culture at the University of Washington.

MIKE BAILEY was elected to the Acoustical Society of America's Executive Council, beginning his term in May 2014.

LAWRENCE CRUM received the William and Francis Frye Honorary Fellowship from the International Society of Therapeutic Ultrasound and was named Senior Visiting Fellow at Magdalen College, University of Oxford.

future generations

of scientists + engineers

The Applied Physics Laboratory advances the education mission of the University of Washington by teaching, advising, and mentoring students. Our researchers hold 54 academic/faculty appointments across 12 UW departments, the greatest number of these in the College of Engineering and the College of the Environment.

The diversity of APL-UW researchers' expertise translates to a wide array of UW course offerings, from *Probability + Random Processes* (Electrical Engineering) to *Arctic Marine Vertebrate Ecology* (Aquatic + Fishery Sciences). Twelve APL-UW faculty hold 'without tenure' appointments that integrate them even more closely into the UW academic faculty.

student achievements p. 62

Our faculty researchers guided the advanced degree programs of nearly two dozen students over the past biennium. Scores of graduate and undergraduate students every year are integrated directly into sponsored research projects, where they gain specialized training, experience, and broad professional support.

Our researchers demonstrate the many contributions of government funded research to society, fulfilling a mission of our research granting agencies. We advance science, technology, engineering, and math education programs, disseminate knowledge to the research community as broadly as possible, and share cutting edge science with the public.

The **Hardisty Undergraduate Scholarship**, established in 1997, provides funds for students to work with an APL-UW staff mentor on a funded research project in addition to a book award. The **Boeing/APL-UW Undergraduate Scholarship** for Women, Under-represented Minorities, and Economically Disadvantaged Students is an exact parallel to the Hardisty program. Since 2004 this scholarship has been funded by generous grants from The Boeing Company.

2013 + 2014

hardisty scholars	department	advisor
BRIAN auf der SPRINGE	Electrical Engineering	Brian Marquardt
ROBERT WICKS	Computer Science	Tim Elam

boeing scholars	department	advisor
STEPHANIE CHU	Bioengineering	Pierre Mourad
ANNIE ZWASCHKA	Neuroscience	Bryan Cunitz + Mike Bailey
ANNA JOY McCLENNY	Microbiology	Barbrina Dunmire + Mike Bailey

All scholars work on an hourly basis in their mentor's laboratory. They are integrated into the research process, treated as *de facto* graduate students, and make significant contributions to the funded projects.

To develop the next generation of researchers in the U.S. Navy core capability of sonar signal processing, the Office of Naval Research sponsors programs at APL-UW to support investigators/advisors and their graduate students.

TOMMY POWERS and **SCOTT WISDOM**, both doctoral researchers in electrical engineering, are advised by **DAVID KROUT** and **JAMES PITTON** on ONR-funded projects in active and passive sonar signal processing. Their thesis topics focus on multi-objective sensor management and nonstationary stochastic processes for passive sonar signal processing. These projects continue the long record of APL-UW research faculty training graduate students in skills germane to Navy applications. David Krout, himself a graduate student a decade ago in the ONR-sponsored program, is a clear example of how the program maintains a pipeline of researchers for U.S. Navy needs.

cultivating research skills

A highlight for many undergraduate students mentored by APL-UW faculty is to prepare and present posters at the annual UW Undergraduate Research Symposium.

Oceanography major **NATASHA CHRISTMAN** is interested in how climate change and increasing anthropogenic stressors impact local water quality. Her focus, with mentor **JAN NEWTON**, is on Bellingham Bay, where extremely low oxygen concentrations are a recurring phenomenon. Natasha used a time series of monitoring data and manipulative experiments to determine the dynamics of oxygen depletion. She reports that tidal cycling displaces water layers in the bay. And while temperature variation has little effect on water column respiration, organic carbon stimulates oxygen consumption. She concludes that recurring hypoxia in Bellingham Bay is particularly sensitive to anthropogenic nutrient inputs and organic matter loading.

Civil Engineering major **MADDIE HUBBARD** conducted a series of experiments with lab-made kidney stones — small cylinders cast with plaster of differing hardness. These experiments, encouraged by mentor **ADAM MAXWELL**, are an important part of determining whether burst wave lithotripsy treatment can break stones into fragments small enough to pass naturally through a patient's urinary tract. Maddie subjected the cast stones to ultrasound then determined their fragment size distribution by weight. Her work reports that the treatment can erode stones of various sizes and hardness into uniformly sized fragments and provides useful data to plan lithotripsy treatments.

p. 40

two students, working in center for industrial + medical ultrasound labs, presented findings from ultrasonic kidney stone research

Diagnostic ultrasound is an inexpensive, noninvasive, and radiation-free method to determine a patient's kidney stone size. Sonographers, however, often overestimate stone size. Microbiology major **ANNA McCLENNY** explored with mentors **BARBRINA DUNMIRE + MIKE BAILEY** whether the acoustic shadow cast behind the stone during ultrasonography was a more accurate measure of its size. She tested experienced ultrasound operators in a series of experiments with real stones in a model collection space. She reports that stone size accuracy was greater when calculated from measures of the acoustic shadow than by standard methods. Further, size estimate errors increased with imaging depth for all ultrasound measurement modalities except when based on the acoustic shadows cast by stones.

Computer engineering major **NAKUL MALHOTRA** tackled a complex nearshore oceanography problem — the dynamics of a saltwater wedge in a tidal estuary — with mentor **CRAIG McNEIL**. Measurements collected over five years from remote sensing platforms and autonomous underwater vehicle missions in the Columbia River estuary were examined by Malhotra to find times of overlap. He then traced how the remote sensing data reveal surface manifestations of the salt wedge pushing into the river along its bottom. He reports that these data can be used to improve numerical simulations of tidal estuary dynamics based on the remote sensing of surface signatures generated by features and processes at depth.

photo: David Ryder

JAMES GIRTON and **BYRON KILBOURNE** mentored double math and physics major **JESSE ASHWORTH-MARIN**, who studied data collected by EM-APEX floats over five years of deployments in Drake Passage. These profiling floats measured pressure, temperature, salinity, and horizontal currents in the Antarctic Circumpolar Current. Jesse's research problem was to develop a mathematical and physical model of float motion that estimates the water's vertical velocity — challenging to measure but important for understanding how momentum and energy are exchanged between the atmosphere and ocean floor. His model accounts for float buoyancy and drag during the vehicle's profiling excursions. The method he developed shows that by knowing how fast the float is expected to move and how fast it is observed to move, the vertical motion of the water itself can be estimated.

sharing science

Believing that there is no substitute for an authentic face-to-face student–scientist mentoring experience, **LAURENCE TOMSIC** organizes an annual science fair at his childrens' K–8 school. He enlists the volunteer support of many APL-UW scientists and engineers to visit classrooms before the fair to inspire and guide projects, serve as judges during the event, and engage with educators all along the way. In 2015, the fifth consecutive year, student participation reached 60% of total enrollment, science project quality rose, and educators, parents, and representatives from local high-tech industries applauded the event's success.

Software engineer **LINDA BUCK** organized a day at APL-UW for fifth graders from the Seattle Girls' School—a STEM middle school with a diverse and economically disadvantaged student body. APL-UW women—physicists, oceanographers, and electrical engineers—took the girls on a tour of lab facilities and answered a lot of questions. The girls heard how the women chose careers in research and where they found encouragement and support along the way. Buck considers herself fortunate to have been guided by many women in science during her career and sees these outreach events as a way to "pay it forward."

Before and after a 39-day cruise to study the flow through the Samoan Passage, the APL-UW science team, organized by **JOHN MICKETT**, shared their passion for oceanography with the Samoan community. Dozens of girls from the Samoa Victim Support Group—a shelter for abused children—were invited on board the R/V *Thompson* to see how scientists study the very deep ocean. They were encouraged to decorate styrofoam heads and visualize them as receptacles for their problems. During the cruise the decorated heads were attached to the ship's CTD and plunged to 5000 m; squeezed of their contents, the shrunken heads were given back to the girls when the researchers returned to port. Before leaving Samoa, the Head of State, His Highness Tui Tupua Tamasese Mea'ole, visited the *Thompson*, was briefed on the research conducted in this fascinating part of the Pacific Ocean, and was presented a vial of salt precipitated from Antarctic Bottom Water collected at 5000 m in the Samoan Passage.

In 2015 there was record participation at the **10th Annual Polar Science Weekend**. The partnership between APL-UW and Pacific Science Center in Seattle began a decade ago and has grown with the participation of several UW units and organizations including the U.S. Antarctic Program, U.S. Coast Guard, and NOAA, to name a few. This year over 200 scientists, students, and other volunteers presented hands-on activities, live shows, and interactive exhibits to more than 11,000 visitors during the three-day event.

Sixty-five students from UW Oceanography 102—*The Changing Oceans*—volunteered to run the *Salinity Taste Test* booth, and 35 from UW Fisheries 464—*Arctic Marine Ecology*—staffed the *Narwhal Mysteries and Arctic Seals* and *Disappearing Ice* exhibits. The fisheries students also participated, pre-weekend, in a science communication workshop taught by Pacific Science Center professionals to hone their skills presenting science to the public. The dedication of **HARRY STERN**, event organizer, and hundreds of volunteers has made Polar Science Weekend a long-term and growing success.

supporting aspiring investigators

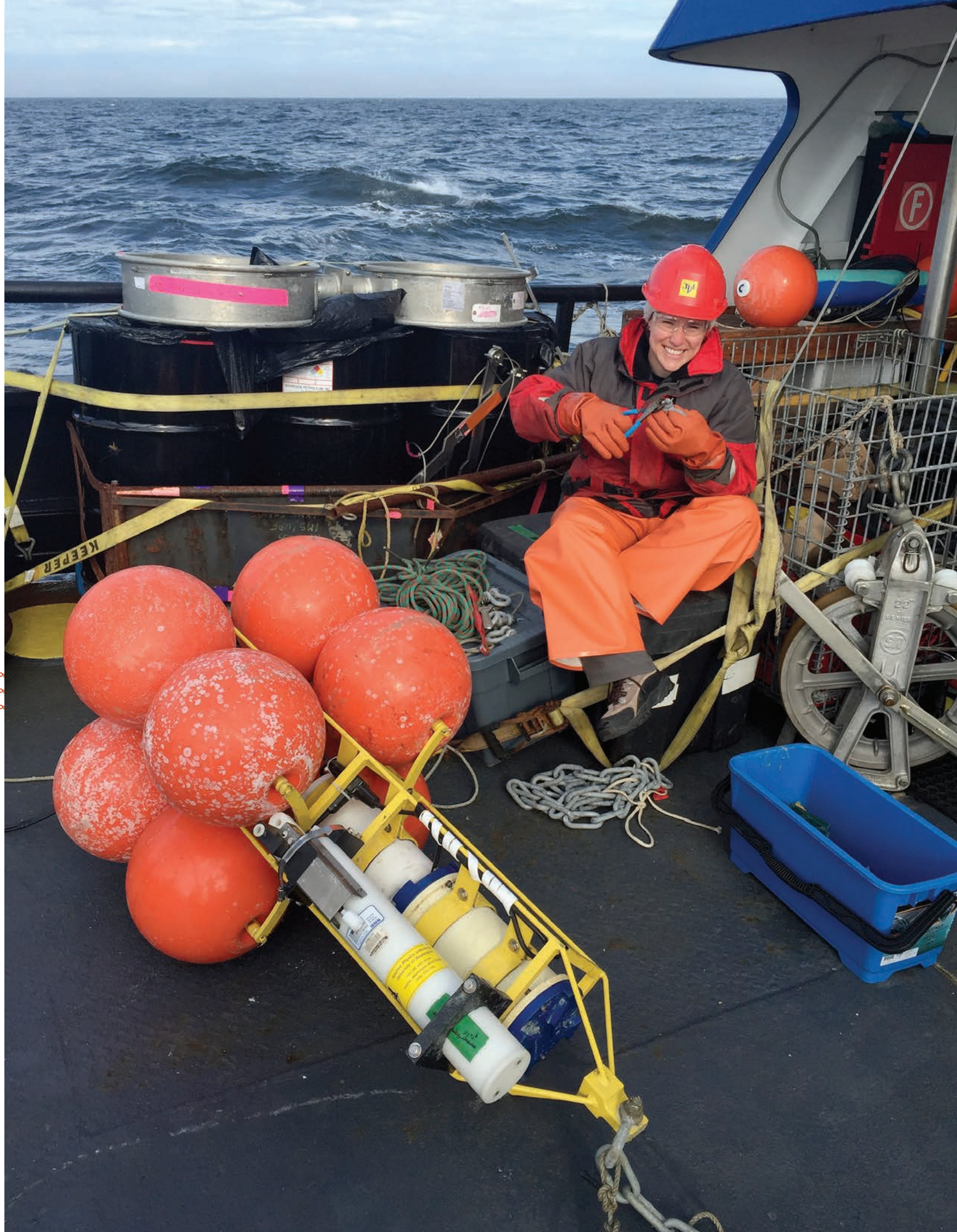
The **SCIENCE + ENGINEERING ENRICHMENT + DEVELOPMENT** postdoctoral fellowship program was established in 2014. Two fellowships are available each year and all fellows are supported by the program for two years. SEED fellows have research goals aligned with APL-UW areas of expertise and define their research programs in conjunction with an APL-UW principal investigator mentor.

"Postdoctoral researchers make significant contributions and often become long-term additions to the science and engineering staff. SEED aims to increase our number of postdocs and to give these new researchers flexibility to set their goals within the Lab's areas of focus and expertise."

– Physicist Kevin Williams

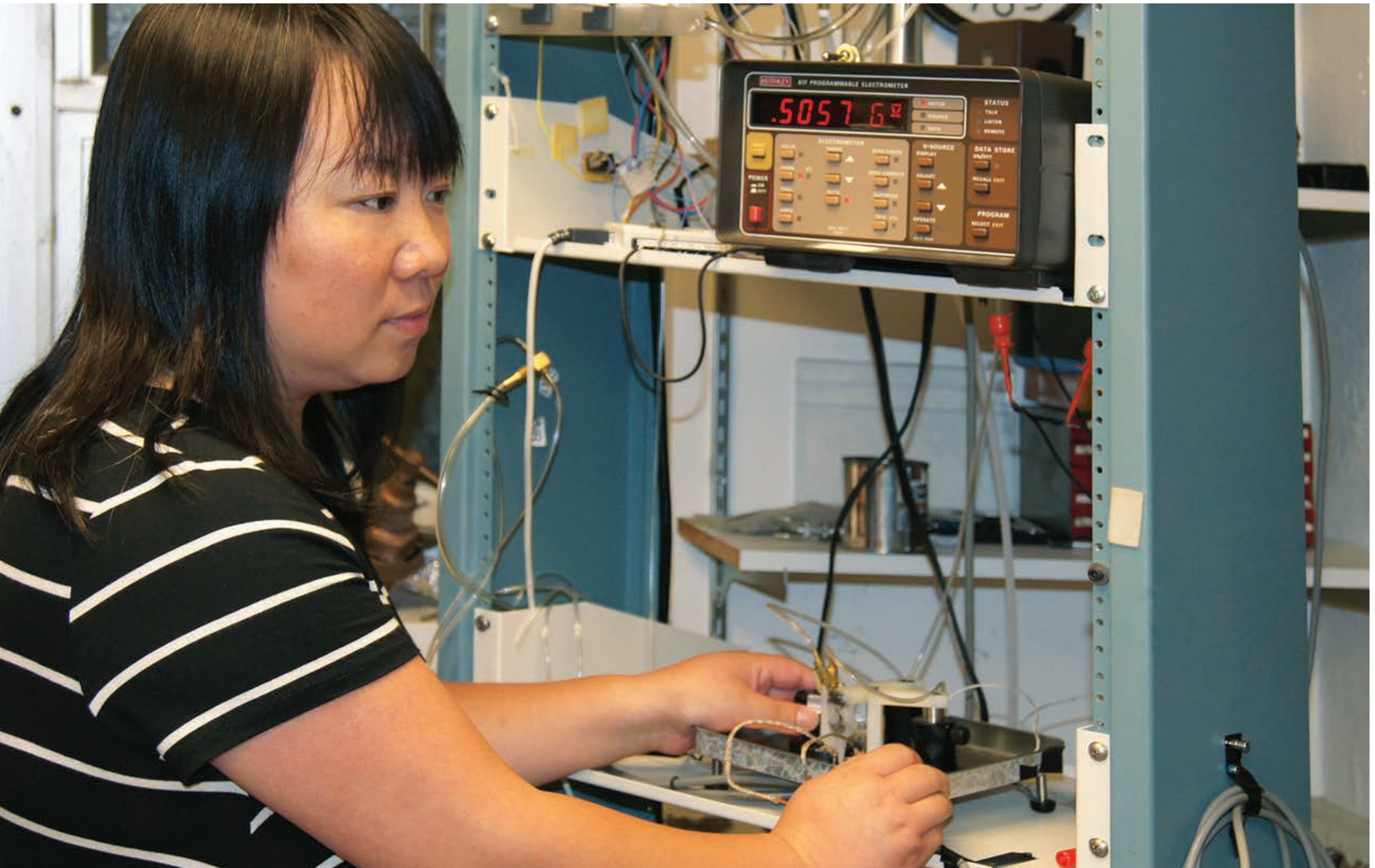
Understanding that much contemporary science is conducted through interdisciplinary collaboration, **MELANIA GUERRA** is doing just that in her study of underwater noise budgets in arctic seas. At APL-UW she is mentored by **KATE STAFFORD**, expert in acoustic studies of marine mammals in the Arctic. Melania is pursuing the question of how anthropogenic noise in the region is contributing to the overall underwater soundscape.

Warmer temperatures and longer ice-free summers have increased shipping traffic and seismic surveys used by oil and gas exploration. What are the spatial and temporal distributions of human and marine mammal underwater sounds? What impact may a noisier ocean have on marine mammals and how might they adapt? "APL-UW is an ideal place to tackle such complex problems, because there are so many experts probing arctic science from different perspectives," says Guerra.



For **DANLING WANG** the SEED fellowship is an opportunity to develop a non-invasive, pain-free, simple, and low-cost test to detect disease in diabetes patients. As a doctoral researcher she developed sensors based on semiconducting nanomaterials to detect trace amounts of vapor from explosive materials.

Now she is applying that expertise under the mentorship of **BILL ASHER** and **ERIC THORSOS** to create a sensitive, rapid response, solid state sensor that analyzes a patient's breath for acetone, a sign of insulin deficiency. During the fellowship period, she hopes to develop a feasible sensor, initiate a research program with national mission agency funding, and pursue an applied research program with an industrial partner to transition the sensor technology to a product used daily in home healthcare.



AARON MARBURG joined the SEED fellowship program in 2015 and is mentored by **ANDY STEWART** in the Ocean Engineering Department. He is working to apply his expertise in small, flying vehicles to underwater robots. APL-UW's advances in autonomous undersea vehicles (gliders, floats) and remotely operated vehicles attracted him to the fellowship. These platforms also have limitations that he seeks to overcome. Aaron wishes to develop an AUV that can 'hover' underwater with situational awareness of its environment.

The core problem is to combine visual and other sensors on the vehicle to enable navigation and interaction within the changing environment while remaining on station for weeks, months, or years. Such a vehicle could observe seafloor hydrothermal vent sites, a section of reef, or life under an ice shelf. Marburg's dream application: "To perform monitoring of a whale fall, providing regular, long-term observations of the progression of species at the site."

"My interest is in developing systems that address real scientific needs, rather than considering abstract technical problems."

– SEED Fellow Aaron Marburg

AARON DONOHOE is an atmospheric radiation specialist and theoretician who studies global scale climate dynamics. For example, how much of the sun's energy is absorbed by the Earth's atmosphere and surface, and how may it change in a warmer world? His current focus is to model the causes of arctic sea ice retreat from year to year and determine whether the mechanisms involved have a role in the long-term response of sea ice to global warming.

He was attracted to the research expertise in arctic climate physics at the Polar Science Center and particularly to **AXEL SCHWEIGER**'s atmosphere–sea ice interactions research. During the fellowship he has engaged with many scientists at the Laboratory and in UW departments to broaden his perspective on arctic climate system dynamics. "The freedom to explore new ideas has been incredibly beneficial to my progress as a scientist," says Donohoe.

photo: Richard Baker

student achievements

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

CHRISTOPHER BASSETT, Mechanical Engineering, Ph.D., 2013
Ambient noise in an urbanized tidal channel
Jim Thomson

ROXANNE CARINI, Civil Engineering, M.S., 2014
Estimating energy dissipation due to wave breaking in the surf zone using infrared imagery
Chris Chickadel

JOSH D. CARMICHAEL, Geophysics, Ph.D., 2013
Melt-triggered seismic response in hydraulically active polar ice: Observations and methods
Ian Joughin

NAN-HSUN CHI, Oceanography, M.S., 2013
Variations in the surface mixed layer heat budget during Madden–Julian oscillation events in the central Indian Ocean
Ren-Chieh Lien + Eric D'Asaro

BETH CURRY, Oceanography, Ph.D., 2013
An observational study of Davis Strait transports
Craig Lee

DAVID DALL'OSTO, Mechanical Engineering, Ph.D., 2013
Properties of the acoustic vector field in an underwater waveguide
Peter Dahl

R. WALT DEPPE, Mechanical Engineering, M.S., 2014
Hypoxic intrusions to Puget Sound from the Pacific Ocean
Jim Thomson

HAYLEY DOSSER, Oceanography, M.S., 2013
Properties of near-inertial waves in the Arctic Ocean from year-round observations
Luc Rainville

TAMAS GAL, Electrical Engineering, M.S., 2014
Design of a C-band conformal phased-array antenna for airborne synthetic aperture radar
Gordon Farquharson

ANDREW GANSE, Geophysics, Ph.D., 2013
Uncertainty and resolution in full-waveform, continuous, geoacoustic inversion
Bob Odom

FARZAD HESSAR, Electrical Engineering, Ph.D., 2014
Spectrum sharing in white spaces
Payman Arabshahi

SINA NIA KOSARI, Electrical Engineering, Ph.D., 2013
Haptic virtual fixtures for robotic surgery
Payman Arabshahi

KALYN QUINTIN MACINTYRE, Aquatic + Fishery Sciences, M.S., 2014
The distribution and timing of bearded seal *(Erignathus barbatus)* vocalizations reflect changing environmental conditions in the Bering, Chukchi, and Beaufort seas
Kristin Laidre

BROOKE MEDLEY, Geological Sciences, Ph.D., 2013
Airborne radar and ice core observations of snow accumulation in West Antarctica
Ian Joughin

ANDREW PICKERING, Oceanography, Ph.D., 2014
Investigation of the spatial and temporal structure of internal waves
Matthew Alford

J. PAUL RINEHIMER, Civil Engineering, Ph.D., 2013
Tidal flat thermodynamics
Jim Thomson

FREDRIK RYDEN, Electrical Engineering, Ph.D., 2013
Real-time haptic interaction with remote environments using non-contact sensors
Andy Stewart + Payman Arabshahi

JULIANNA SIMON, Bioengineering, Ph.D., 2013
The thresholds and mechanisms of tissue injury by focused ultrasound
Michael Bailey + Lawrence Crum

ALEXANDER SOLOWAY, Mechanical Engineering, M.S., 2014
Noise from shallow underwater explosions
Peter Dahl

ANDREW WHITE, Geophysics, Ph.D., 2013
Underwater acoustic propagation in the Philippine Sea: Intensity fluctuations
James Mercer

SCOTT WISDOM, Electrical Engineering, M.S., 2014
Improved statistical signal processing of non-stationary random processes using time-warping
James Pitton

SHUANG ZHANG, Oceanography, Ph.D., 2014
Nonlinear internal waves on the Washington continental shelf
Matthew Alford

SETH ZIPPEL, Civil Engineering, M.S., 2014
Wave breaking turbulence at a tidal inlet: Shoals, currents, and winds
Jim Thomson

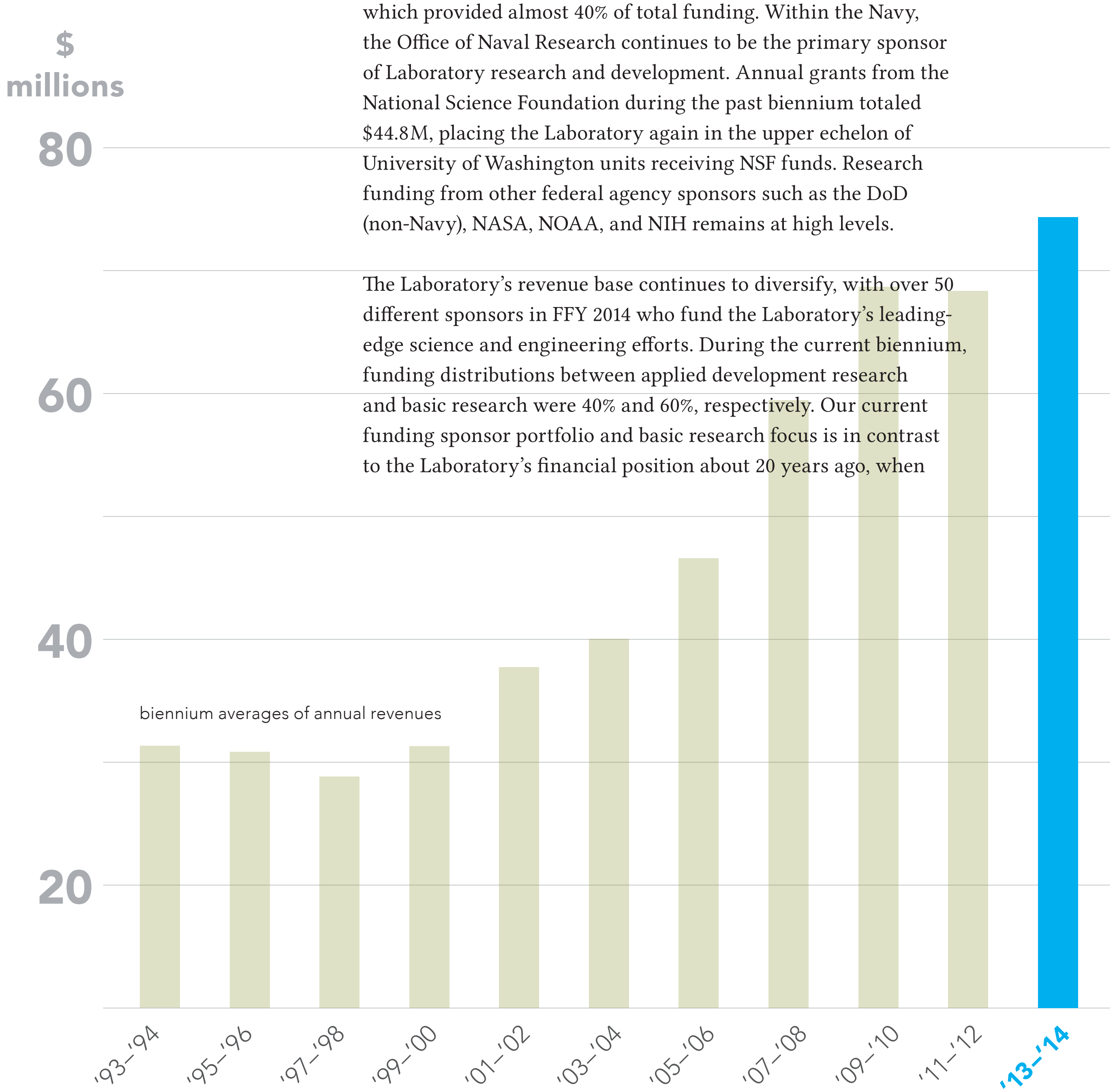
financial health

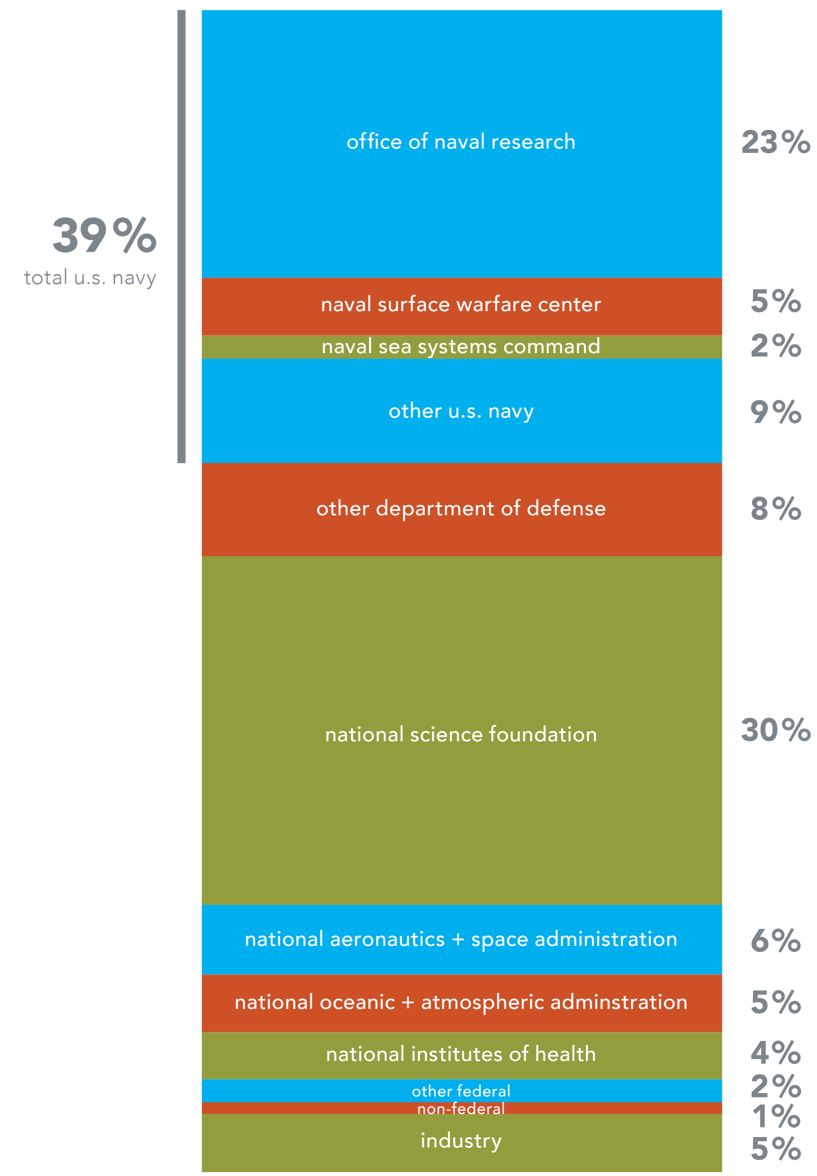
The Applied Physics Laboratory continues to be in a strong financial position. For Federal Fiscal Years 2013 and 2014 grant and contract awards received by APL-UW resulted in a new biennium record. During this period the Laboratory's total awards were $148.7M, exceeding the previous level of $136.4M for FFYs 2011 + 2012.

The Laboratory's strategic DoD partner remains the U.S. Navy, which provided almost 40% of total funding. Within the Navy, the Office of Naval Research continues to be the primary sponsor of Laboratory research and development. Annual grants from the National Science Foundation during the past biennium totaled $44.8M, placing the Laboratory again in the upper echelon of University of Washington units receiving NSF funds. Research funding from other federal agency sponsors such as the DoD (non-Navy), NASA, NOAA, and NIH remains at high levels.

The Laboratory's revenue base continues to diversify, with over 50 different sponsors in FFY 2014 who fund the Laboratory's leading-edge science and engineering efforts. During the current biennium, funding distributions between applied development research and basic research were 40% and 60%, respectively. Our current funding sponsor portfolio and basic research focus is in contrast to the Laboratory's financial position about 20 years ago, when the U.S. Navy provided over 90% of the Laboratory's funding and the ratio between applied science and fundamental research was approximately 65% to 35%. The current percentage balance between applied and basic research reflects growth in important fundamental research areas.

Reductions and uncertainties in federal research budgets and delays in research funding could negatively impact the Laboratory in coming years. Nevertheless, APL-UW remains committed to ensuring that the long-term investments in it by the U.S. Navy and federal government are applied to national strategic and technical needs, and to preserving our ability to respond effectively and efficiently to present and future Navy, national defense, and government research and development needs.





biennium percentages for FFY2013 + FFY2014

publishing productivity

APL-UW scientists share their discoveries by publishing research results in books and journal articles as well as by participating in conferences and workshops. The number of papers authored by APL-UW scientists appearing in the peer-reviewed literature is another indication of the breadth and impact of the Laboratory's research programs.

2014 articles in journals, reports, books + book chapters

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