2022

UNIVERSITY of WASHINGTON

Applied Physics Laboratory

apl-uw

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

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

contents

ANNUAL

Scientific discoveries

Engineering innovations

Solutions for regional, national, and worldwide problems

OCEANOGRAPHY · POLAR SCIENCE · OCEAN ACOUSTICS · MEDICAL + INDUSTRIAL ULTRASOUND · AIR-SEA INTERACTIONS · ENVIRONMENTAL REMOTE SENSING · ELECTRONIC SYSTEMS · OCEAN ENGINEERING · CLIMATE SCIENCE · AUTONOMOUS SYSTEMS · MARINE ENERGY · SIGNAL PROCESSING

welcome from the executive director

KEVIN WILLIAMS

In our individual lives and as part of an organization, there are occasions when it is important to step back, take a deep breath, and assess the future with past events still in clear view. The course of the pandemic forced a fundamental rearrangement of our personal and professional lives. Many changes were readily apparent. Some will only be realized as we move forward. The truth is that individually and as an organization we are moving forward and continue to make progress to fulfill APL-UW's mission. This Annual Report shares, in part, that truth.

I hope that this report makes clear the Laboratory's continuing commitment to doing difficult things and doing them well. Whether in our internal lab spaces or in remote settings, our researchers are always addressing new questions and tackling technical challenges. They seek new ways to engage current technology, and design new solutions that can be deployed to reach fundamental science and applied research goals.

Another truth about the Laboratory, brought into sharper focus by the challenges of the pandemic, is the sacrifice and dedication of all in our community to meet the expectations of our research sponsors and colleagues. As you read of our efforts over the past year, please understand that there is a great deal more to each and every story. This is only the tip of the iceberg. The unseen ninety percent is the dedication of every APL-UW staff member to be part of an organization that gets every job done well. This spirit is what has always drawn me to the Laboratory. I believe you will find the stories of accomplishments and ongoing efforts shared in this report prove that we were resilient against the challenges of the past couple of years and are moving forward with our values and purpose strengthened.

productivity + new directions

One way that we measure our productivity is by contributions to the peer-reviewed literature. Another is our ability to garner interest and win support from research sponsors to pursue new directions based on a long record of scientific and technical expertise. Here, we draw special attention to several high-impact papers in the scientific literature and significant advances in research and development programs.

A team from the Laboratory's Center for Industrial + Medical Ultrasound and their multi-institutional collaborators continue to generate wide interest with the demonstration of an ultrasonic kidney stone treatment system. New theoretical, laboratory, and human clinical trial reports landed on prominent journal covers during 2022.

The Laboratory's polar scientists are advancing our understanding of ice-covered environments, some using observations from Earth orbiting satellites or melt probes diving into ice sheets, and others from the perspective of the most iconic Arctic mammal — the polar bear.

We are happy to welcome a new capable platform that extends the Laboratory's ability to pursue underwater acoustics research programs, reinvigorating research in high-frequency imaging sonars and supporting new areas of collaborative inquiry.

a specialized research vessel joins the APL-UW fleet

R/V ***Lee Thompson*** entered service in early 2022 to support acoustic sensor development. The new vessel is named in dedication to the late Lee Thompson, co-founder of the spin-off company BlueView Technologies (now Teledyne Marine) and inventor of blazed array sensor technology. His return to APL-UW in 2015 renewed imaging sonar research and development at the Laboratory.

The open deck, 30-foot catamaran has an eye-catching yellow gantry with a 3500-pound lift capability standing over a large moon pool. Designed for flat-water, low-speed operations, the ***Thompson*** is powered by twin electric outboards. These provide excellent speed control from 0 to 5 knots, and their hush quiet operation enables vibration-free acoustic sensor testing without the background noise of rumbling engines.

Recessed in the moon pool are four mounting points that allow payloads to be locked firmly into position relative to the onboard GPS system. Further capabilities include bow and stern side thrusters, a Garmin chartplotter with hydraulic autopilot control, and a custom course planning program to interface with the chartplotter. The result is a semi-autonomous acoustic scanning platform that can target specific positions and run identical courses day after day to test new sonar systems and other acoustic sensors.

Senior Principal Engineer **STEVEN KAHLE** reports that the vessel's schedule is committed already to projects that will keep it in continuous service for several years. R/V ***Lee Thompson*** was built entirely by APL-UW staff and students based on a concept from Principal Engineer **DAVID DYER.** Working through a season of record rain and cold weather on the fabrication project, the team delivered the vessel into service in March.

Scientists have documented a new subpopulation of polar bears living on the southeastern coast of Greenland. This important discovery, which received cover feature treatment in the 17 June issue of ***Science***, came as a complete surprise to lead author **KRISTIN LAIDRE** and the international research team.

Laidre, a Principal Oceanographer in the Laboratory's Polar Science Center, has studied polar bears for over 15 years. Sea ice is a polar bear's platform for life — to travel, hunt, and reproduce. Previous collaborative studies analyzed decades of sea ice data to calculate the seasonal length of sufficient sea ice habitat to support the 19 polar bear subpopulations living in the circumpolar Arctic. Over the past several decades of declining sea ice extent and volume, this season has grown shorter by several weeks in most regions.

isolated, genetically distinct polar bear population discovered

In 2011 Laidre's team began a multiyear project to assess the status of the East Greenland bear subpopulation. Combining GPS movement data from collared bears, satellite observations of sea ice conditions, and indigenous knowledge, they were intrigued by the behavior of bears in the southernmost portion of the East Greenland coast. Even though there are only four months of good sea ice habitat here each year, the bears did not venture far from the fjords and marine-terminating glaciers that define the region. Isolated by the Greenland Ice Sheet, mountain peaks, open water, and swift coastal currents, the bears use the fjord-clogging mélange of freshwater ice that breaks from glacier fronts as a hunting platform when the sea ice disappears each spring.

While this isolated subpopulation has found refuge in a warming Arctic with diminishing sea ice, its glacial mélange habitat is uncommon across the Arctic and is itself changing in response to climate warming. Continued monitoring of this distinct subpopulation is critical.

surprising decline of arctic sea ice in just 3 years

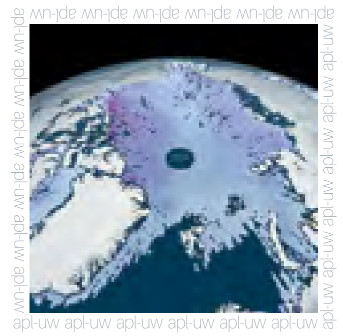


image: NASA Scientific Visualization Studio

Prior to its 2018 launch into orbit, Polar Science Center researchers led science definition teams for NASA's second generation Ice, Cloud, and land Elevation Satellite. And since, they have collaborated with the large community of scientists interpreting ICESat-2's precise measurements of elevation spanning the Earth's surface from pole to pole.

Surprising decreases in snow depth and sea ice thickness have been observed in just the first three years of the ICESat-2 mission. Senior Principal Scientist **RON KWOK** and co-author Sahra Kacimi at the Jet Propulsion Laboratory reported earlier this year that springtime (annual maxima) snow depth and sea ice thickness decreased by over 2 cm and nearly 30 cm, respectively, since 2018.

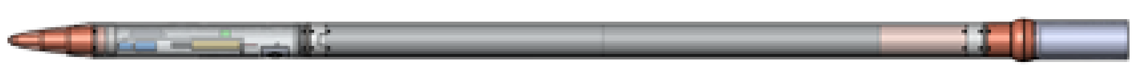
Obtaining measurements of snow-covered floating sea ice from Earth orbiting satellites is a challenge. The new, unexpected findings of recent, rapid snow and sea ice thinning are made possible by combining independent altimeter measurements from the ICESat-2 lidar and CryoSat-2 (European Space Agency) radar. The lidar measures the air–snow interface while the radar measures the snow–ice interface above the sea surface. Differencing the concurrent products provides a new, accurate assessment of snow depth and sea ice thickness trends across the Arctic.

Kacimi and Kwok placed the past three years in a broader context by comparing derived sea ice volumes from the ICESat-2 observations with those from satellite missions extending back to 2003. Since then, an astounding one-third of the maximum winter sea ice volume has disappeared from the Arctic.

on(down)ward to find the oldest ice on earth

The Ice Diver team at APL-UW has a successful record of developing melt probes that descend through glacial ice using modest amounts of electrical power. Logistically, they are very light, allowing researchers to reach deep into ice sheets to make novel observations at low cost.

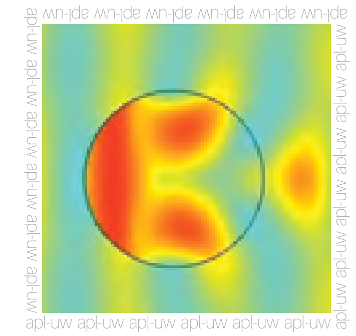
The team's current mission is part of a multi-institutional effort, the Center for Oldest Ice Exploration (COLDEX) Science and Technology Center, funded by NSF. They are designing and fabricating probes to explore ancient ice beds several kilometers deep in East Antarctica. "Our aim is to find and sample some very old and deep ice that preserves climate records from a poorly understood shift in Earth's climate about one million years ago," explains Senior Principal Physicist **DALE WINEBRENNER**.



In 2014 the team sent expendable probes to a record depth of 400 m on the Greenland Ice Sheet. Based on this classic melt probe design, which maintains connection to the surface and electrical heating supply through wires spooled inside the vehicle that unwind during descent, the COLDEX Ice Diver probes are designed to reach 3000 m. On board are optical sensors, developed by collaborator Ryan Bay at the University of California Berkley, to log dust particles. Because the atmosphere was dustier during past, colder epochs in Earth's history, scientists can infer ice age versus depth. Winebrenner adds, "We will also deploy optical fiber from the Ice Diver as it descends and use new commercially available technology to measure the depth profile of temperature in the ice sheet, and from that infer geothermal fluxes that are presently poorly understood."

Work continues to fabricate six nonrecoverable probes that will be deployed in reconnaissance missions in upcoming field seasons to identify promising sites in East Antarctica to later core drill for the most ancient ice on Earth.

editorial praise for ultrasonic kidney stone treatment studies



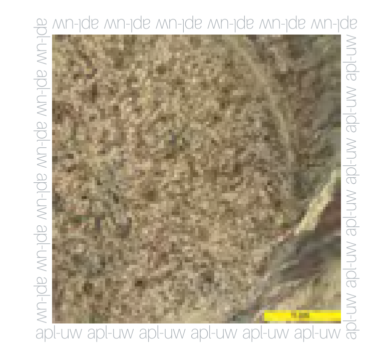
Both the *Journal of the Acoustical Society of America* and the *Journal of Urology* gave special notice this year to reports by investigators at the Center for Industrial + Medical Ultrasound and their multi-institutional collaborators. Burst wave lithotripsy treatment of kidney stones continues to generate broad interest from the medical, science, and engineering communities.

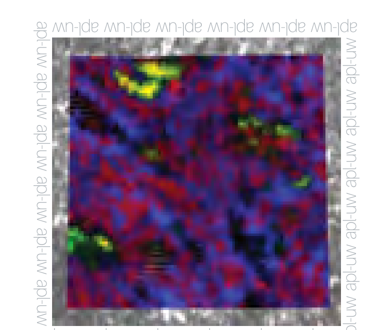
The transcutaneous application of sinusoidal ultrasonic tone bursts has been shown in clinical trials to be easily performed by urologists, and to be minimally invasive and have few side effects for patients. In a recent clinical trial the team reports that patients who were about to undergo surgical intervention for their stones were first treated with burst wave lithotripsy. Treatments limited to only 10 minutes' duration disintegrated 90% of total stone volume to less than 2-mm fragments.

The researchers noted that the trial was limited to a single transducer operating at one frequency. In subsequent numerical modeling and laboratory experiments they explored techniques to maximize the mechanical stress in stones by matching ultrasound frequency to stone size. As reported in *JASA*, when the stone diameter is about one-half the acoustic wavelength, stresses greater than six times the incident pressure are achieved inside the stone. They conclude that an optimal treatment strategy may use a low frequency to initially create high stresses inside a large stone to break it into pieces, then switch to a higher burst wave frequency to erode the multiple fragments to dust.

The team's theoretical, experimental, and clinical advances may benefit early intervention, surgical treatment, and emergency relief for kidney stone patients.

new discoveries in jezero crater, mars





images: NASA/JPL-CalTech

The NASA rover *Perseverance* landed on Mars in early 2021 and began its science mission to study the small-scale structure of rocks in the search for signs of ancient microbial life. One of the instruments on the rover's robotic arm is PIXL (the Planetary Instrument for X-ray Lithochemistry). This summer, the PIXL science team published its first paper in *Science*. Based on the X-ray spectroscopy and other data, they report that a rock in Jezero Crater likely formed from a slowly cooling, thick magma body deep underground that, due to erosion, is now exposed on the surface. Over its history, this igneous rock was altered by the presence of water that once filled the crater.

Senior Principal Physicist **TIM ELAM**, self-identified 'chief spectroscopist' of the Mars rover mission, joined the PIXL team in the early days of mission planning. "PIXL measures the energy of X-rays emitted from the material. And the intensity of each of those X-rays tells us how much of that element is there," explains Elam. "So my job all along has been to model and help design, build, and test the X-ray spectroscopy part of PIXL."

Elam wrote software to process the data beamed back from Mars and provides two interpretive components to the Mars rover science team: converting the PIXL emission spectra to elemental compositions and abundances, and producing a map of the elements distributed on the rock's surface.

"The story of a rock's formation is contained in the set of minerals present because they all form at different temperatures and pressures and under different conditions," says Elam. "Handing off the chemistry and elemental distribution analysis allows geologists to interpret a lot about the history of the rock."

Laboratory professionals are renowned for their ability to field ambitious research programs, particularly at sea, in pursuit of scientific objectives. Successful programs rely on multidisciplinary strategies and collaborative teams, as well as the design, development, and deployment of (often novel) instrumentation in challenging sampling environments.

Here, we share examples of efforts in the field during 2022 that demonstrate the Laboratory's integration of scientific curiosity and motivation, savvy experimental design, and engineering innovation.

from design to deployment

can remnants of melted sea ice precondition arctic ocean freeze-up in autumn?

As daylight hours grew ever shorter this fall on the Beaufort Sea, a multi-institutional team of researchers led by Principal Oceanographer **KYLA DRUSHKA** surveyed as close as possible to the sea ice edge without becoming trapped by its seasonal advance. For one month stretching into early October the team used instruments aboard autonomous vehicles, drifters, aerial platforms, and vessels to understand the dynamics and evolution of near-surface salinity and upper ocean stratification during the transition between summer open water and fall sea ice growth.

During the melt season, Arctic sea ice leaves behind a layer of fresh (less dense) water on the surface that follows the retreating ice edge. The stratification strengthened by this cold, freshwater cap can suppress the upward mixing of warmer subsurface waters. A motivating question for the Salinity + Stratification at the Sea Ice Edge (SASSIE) team is whether surface pools of low-salinity water precondition the ocean for fall freeze-up.

"No research team has concentrated so much sampling effort on the surface and upper one meter of the Beaufort near the ice edge," remarks Drushka. "And the reason we're concentrating here is because the very surface is what can be observed with satellite-borne instruments." She reports that the team aboard R/V ***Woldstad*** found refuge amid the pack ice from the large storm that rolled through Bering Strait in mid-September. They then resumed successful intensive sampling of a restratifying upper ocean just south of the ice edge.

The NASA-funded project joined for the first time APL-UW experts in satellite and in situ sea surface salinity observations with oceanographers who are veterans of Arctic marginal ice zone operations to measure ocean–ice–atmosphere dynamics. Data collected in the Beaufort and subsequent modeling efforts will help them to determine whether the anomalous sea surface salinity signal can be used as a proxy for the timing and spatial pattern of sea ice formation in autumn, thereby increasing the utility of sea ice forecasts based on satellite data products.

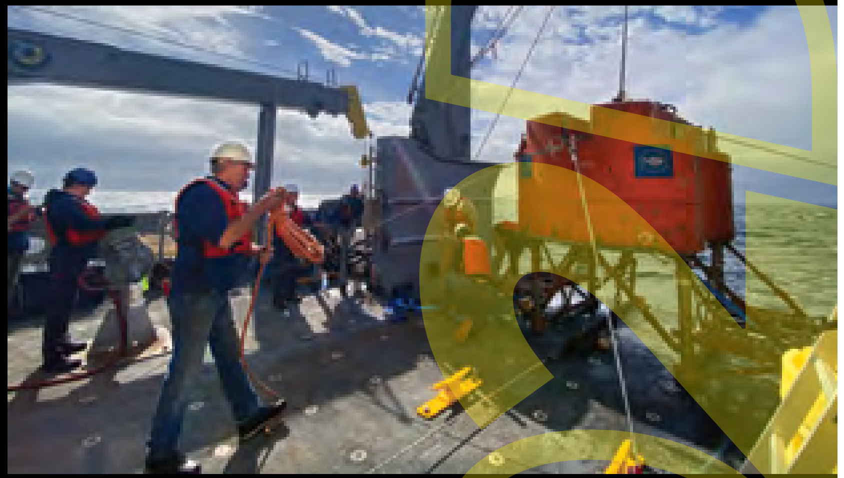
image: Carlyn Schmidgall

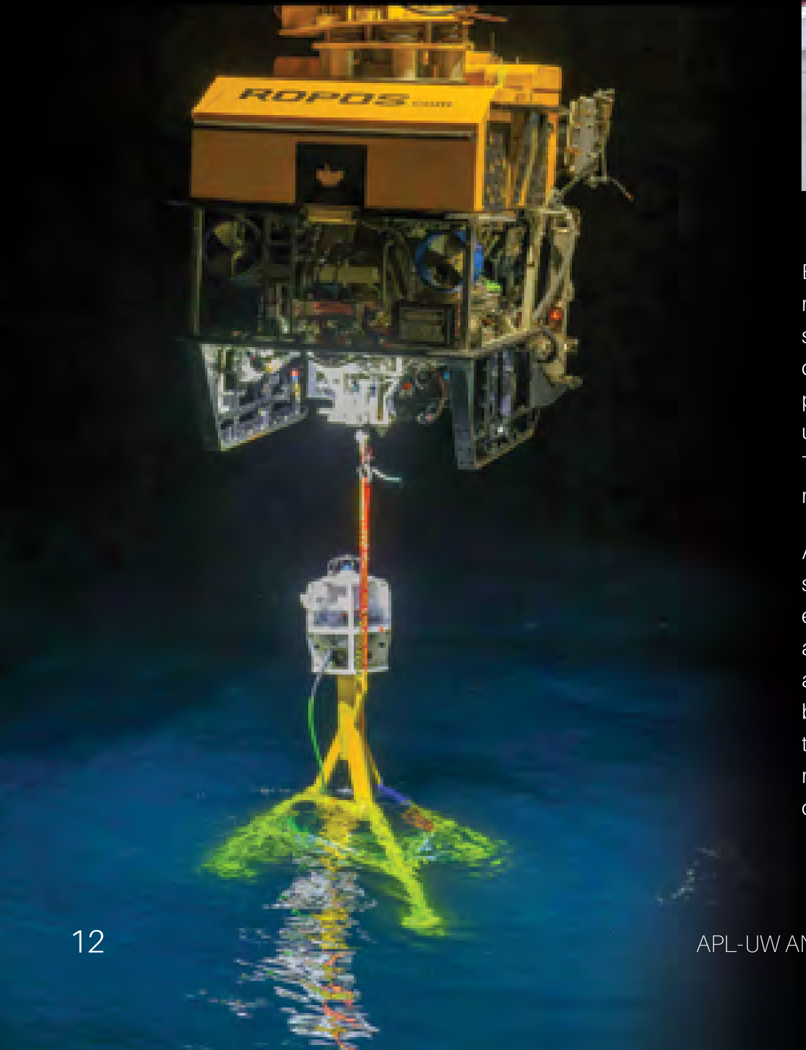
annual expedition requires year-round engineering expertise

Every summer since 2013 the VISIONS expedition to service and enhance the infrastructure, platforms, and individual instruments comprising the Ocean Observatories Initiative Regional Cabled Array (OOI-RCA) requires the greatest concentration of engineering effort of any APL-UW research project at sea.

Before the scientists, engineers, and students set off aboard the University of Washington's R/V *Thomas G. Thompson* for the 45-day cruise this summer, 20 trucks transported over 60 tons of gear from the Seattle engineering lab warehouse to the Newport, Oregon dock. Mobilizing the expedition across five legs accommodates crew changes, and is required to handle the sheer volume of gear and equipment to operate, maintain, and enhance the world's largest ocean observatory.

This year over 200 diverse instruments were recovered from and redeployed on the array's cabled power and communication network. It was also the first time since OOI-RCA commissioning that a complete Shallow Profiler Mooring was recovered and reinstalled. This operation itself required mobilization over two legs to accommodate the extra lifting winches, 7-ton mooring platforms, and thousands of meters of cable on the deck of the global class *Thompson*.





Back at our facilities in Seattle all recovered instruments are refurbished and put through several rounds of testing — in saltwater tanks, under high-pressure conditions to simulate seafloor deployment, and integrated to a lab-based, OOI-RCA specification power and communication network to assure proper behavior under operational conditions when plugged back in to the array. This rigorous testing regime ensures a high operational success rate when the instruments are redeployed the following year.

APL-UW engineers provide critical collaborative support to scientists at the UW and beyond to develop new instruments to expand the OOI-RCA observing capacity. This year, for example, an acoustic array consisting of four tripod platforms was set down across Axial Caldera to detect horizontal seafloor motions caused by expansion of the volcano's magma chamber. Engineers will use the acoustic beacons in the future as navigational aids for planned resident autonomous vehicles that will extend the horizontal range of OOI-RCA observations.

equipping fleets of ocean drones to sense sea surface temperature

Over the course of two sea trials in 2022, researchers are working step-by-step to miniaturize and simplify infrared radiometers used to measure the temperature of the ocean's surface skin layer. Senior Principal Oceanographer **ANDY JESSUP**, who leads the effort, explains that for decades climate scientists studying the fluxes of heat across the air–sea thermal boundary layer have relied on the measurement of ocean skin temperature by IR radiometers. "Obtaining this surface measurement is critical, because even though the temperature difference between the skin and subskin a millimeter below can be small, inaccuracies of only tenths of a degree throw off heat flux estimates by 20 to 40 percent."

A recent convergence of technologies – improving quality of small, commercial radiometers and growing use of robotic ocean-going platforms – makes possible the widespread collection of ocean surface skin temperature data. Until now observations were limited to expensive and complex ship-based IR systems that use a two-point calibration scheme with precision blackbodies and a separate sky measurement to correct for reflected downwelling radiance.

With an assist from the Laboratory's Ocean Engineering Department, the small radiometers were modified to make one-point, in situ calibrations. And when mounted in a tandem down- and up-looking configuration on a research vessel's bow, the system returned ocean surface skin temperature results comparable to 'gold standard' ROSR radiometers.

Now, with continuing support from the NSF Ocean Technology and Interdisciplinary Coordination Program, Jessup is developing a technique to correct emissivity uncertainty with local atmospheric temperature and humidity measurements, eliminating the need for a separate sky measurement. In another step this fall the small radiometers were mounted on the masts of four Saildrones, two with a down- and up-looking configuration and two looking only at the sea surface, operating near a research vessel in the Pacific for 30 days.

"Demonstrating accurate measurements from a single, small instrument that is simply and reliably calibrated will make it practical to collect ocean skin temperature data from many platforms, including robotic surface vehicles, floats, and buoys," adds Jessup. "Skin temperature could become a standard measurement for all ocean-going research."

washington coast
a natural laboratory for joint oceanographic + acoustics research

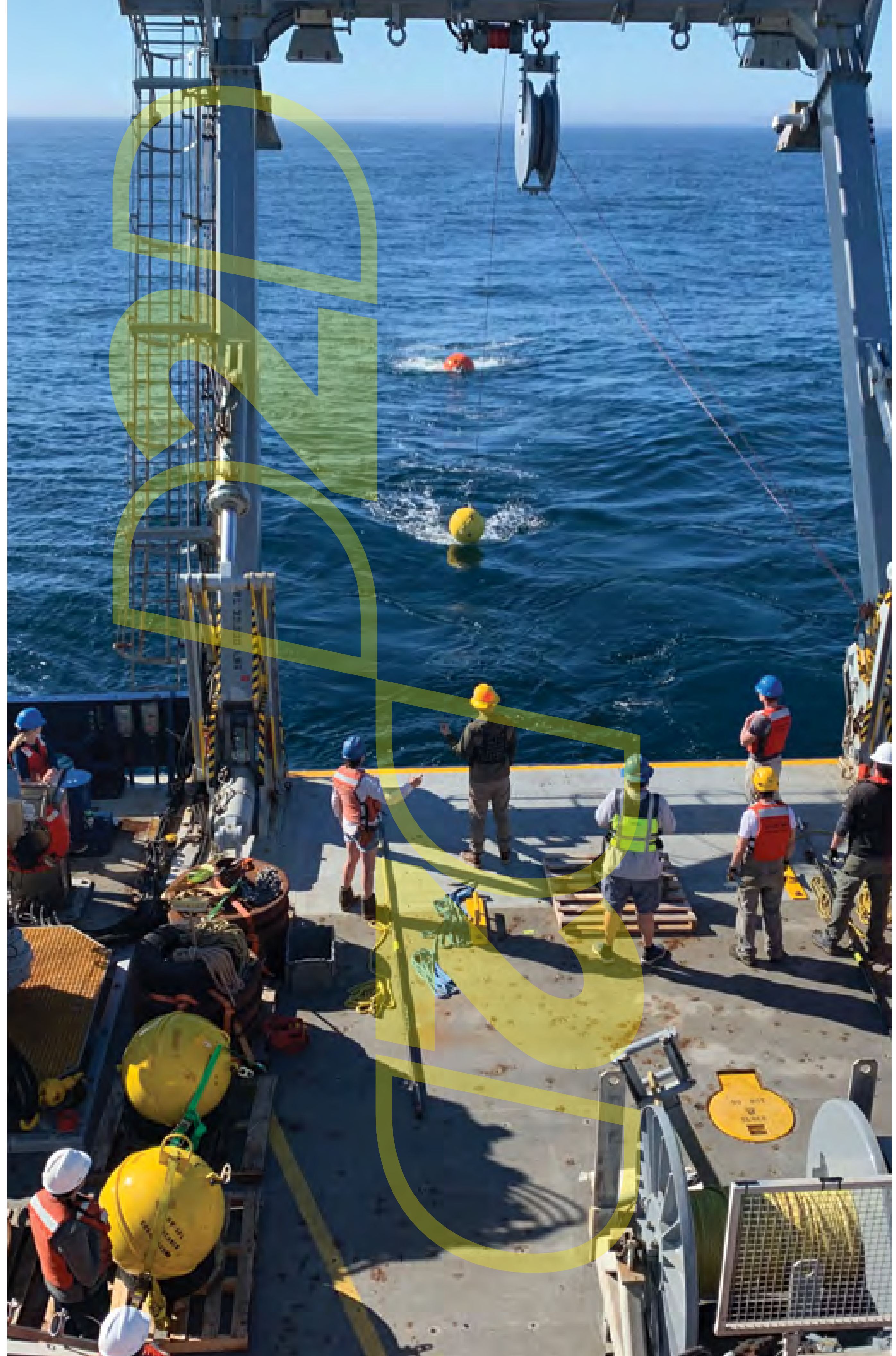
Washington coastal waters are rich with complex temperature and salinity variations that create surface and subsurface acoustic ducts, affecting passive and active sonar operations, especially in the mid-frequency range. At depths of 50–150 m, ducts can trap acoustic energy in broad layers of sound speed minima and channel sound over long distances.

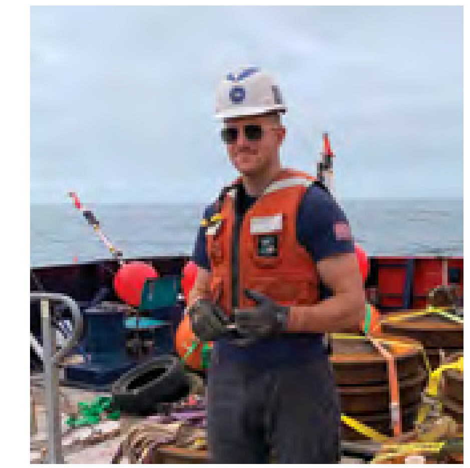
These subsurface acoustic ducts are found frequently in spring and summer when winds on the Washington coast drive upwelling of deep ocean water and push freshwater plumes from coastal rivers offshore. A Laboratory team of ocean acousticians and physical oceanographers designed an intensive at-sea observation program at a site extending 100 km alongshore and 100 km offshore across shelf, slope, and open ocean environments. During several weeks in July and August aboard R/V *Sally Ride*, the team deployed an array of five moorings and ran continuous hydrographic surveys to simultaneously measure acoustic fluctuations and the evolving physical structure of the coastal environment.

The combination of shelf–slope topography and large riverine inputs makes coastal Washington an ideal testbed for similar regions, which are of high interest to the U.S. Navy. With support from the Office of Naval Research's Task Force Ocean initiative, the team leveraged the research infrastructure and long-term observing programs along this stretch of coast to give support and context to their intensive operations. Summer 2022 experiments were designed to integrate historical data, observing technologies, and multidisciplinary academic expertise to advance understanding and prediction of hydrographic controls on mid-frequency acoustics in a representative coastal environment.

Transmission sequences from the Laboratory's ARMS (Autonomous Reverberation Measurement System) set down at 180 m depth offshore were recorded continuously on a line of receiving arrays moored upslope from the source. Moorings were also equipped to measure temperature, salinity, and horizontal velocity throughout the water column, capturing the ducts' vertical structure and lateral advection during the intensive observation period.

The towed vehicle SWIMS (Shallow Water Instrument Mapping System) was developed at APL-UW in the 1990s, and was used here for the first time to support an acoustics experiment. Towed continuously at 3–5 knots and profiling 60–100 m per minute, SWIMS mapped temperature and salinity of targeted water masses along the acoustic transmission paths.





UNDERGRADUATE INTERN PETER TSIRUSHKIN gained hands-on research experience when he joined the cruise in July. Disembarking early to participate in drills, the U.S. Marine Corps reservist and UW physics major assisted with SWIMS operations and the assembly and deployment of moorings. One was a bottom lander set down at 180 m depth equipped with two ambient noise recorders to study bubble plume dynamics due to wind forcing and their relation to ambient noise levels. "It's great to be part of research that will have a direct application to naval operations," says Peter. "The project marries my two passions, science and service."

Back on land and mentored by Principal Physicist **JIE YANG**, Peter is learning the methods to process ocean environmental noise data, teasing out the contributions from wind, rain, and biologics. As classes began in the fall quarter, Tsirushkin and Yang turned their attention to processing and analyzing the summer '22 Washington coast data set.

Environmental noise in the deep ocean differs dramatically from coastal sites for two main reasons: ambient noise generated at the sea surface undergoes reflections between the surface and bottom, and the growth of surface waves in coastal waters depends on wind speed, direction, duration, and fetch. The ambient noise field generated by surface breaking waves, therefore, can be very different from that in the deep ocean. Data from the companion acoustics and oceanographic experiments promise for Yang and her team new quantitative explorations of the ambient noise field in coastal environments.

a return to the great mud patch

An APL-UW team joined their multi-institutional, international colleagues on a late spring 2022 research cruise centered on the New England mud patch. The expedition, funded by the Office of Naval Research, is the most recent effort in this region to characterize the fine-grained sediments and their influence on undersea acoustic propagation.

Senior Acoustician **DAVID DALL'OSTO**, who served as chief scientist on the primary leg of the expedition last spring, explains, "Mud has unique sound speed properties in that it traps acoustic energy. The observations we made here in 2017 were really eye opening, so when we returned this spring we designed experiments to confirm and extend our observing and data analysis strategies to understand the properties of this muddy seabed."

Since 2015, ONR's ongoing Seabed Characterization Experiment (SBCEX) has focused on this portion of the continental shelf about 100 km south of Martha's Vineyard because of its proximity to oceanographic research infrastructure, the region's extensive patches of thick mud sediments, and because it is the site of past and ongoing characterization studies. The overall goals are to probe the geoacoustic properties of marine mud and examine the effect of stratigraphy (sediment layering) on acoustic propagation. "By innovating and comparing a large variety of experimental and inference techniques and methods to a limited region of the mud patch, all the participating investigators are exhausting efforts to understand sound propagation over muddy sediments," comments Dall'Osto.

Experiments were designed to use active impulsive and towed tonal acoustic sources, as well as passive shipping noise. Recording technologies included vertical line hydrophone arrays and ocean bottom recorders. APL-UW's unique contribution to SBCEX has been acoustic vector sensing technology and the analytical methods to infer seabed properties from the vector sensor data.

The Intensity Vector Autonomous Recorder (IVAR), deployed to the seabed, captures four channels of acoustic data continuously — one for acoustic pressure and three associated with an accelerometer to measure acoustic particle velocity, thus sensing the direction of sound and its often overlooked property of kinetic energy. Deployments of a single IVAR in 2017 and 2021 measured the vector properties of active and passive acoustic sources, "... and we discovered a signature of bottom layering. That is, the low-frequency dispersion of the signals shows acoustically transparent mud layers sitting atop harder sediment layers," explains Dall'Osto. The subtle effects of the mud on propagation became more obvious at higher frequencies, and revisiting the mud patch in 2022 gave the team the opportunity to understand the stability of the observed effects.

Experiments this spring positioned two IVARs about 20 km apart along a contour of the continental slope and proximate to busy shipping lanes. New views of sediment layering structure can be inferred from the acoustic data when ship sources pass directly above IVAR. And with hundreds of ship sources up to 100 km distant recorded by IVARs for four weeks, the team is confident that the remote acoustic sensing data can be used to extend a map of sediment properties beyond the boundaries of the mud patch experimental site.

The SBCEX efforts advanced the predictive capability for acoustic propagation, specifically as applied to marine environments with a muddy seabed. Data from these experiments provide invaluable information to invert for the geophysical properties of marine mud in situ, validating theoretical predictions of this unique medium. Importantly, analysis of IVAR data shows that mud properties change with depth and demonstrates the utility of measuring the complete acoustic (vector) field.

l to r: Senior Principal Engineer **PETER DAHL**, Senior Engineer **ERIC BOGET**, and Senior Acoustician **DAVID DALL'OSTO** on R/V *Neil Armstrong*

harvesting energy from tidal flows

Marine energy conversion can harness the natural energy of the marine environment to power electronic systems independent of cabled infrastructure. The Naval Facilities Engineering Systems Command has funded efforts at APL-UW to harvest this largely untapped resource for strategic and operational advantage.

predictable, reliable power

Agate Passage, a high-current tidal strait in Puget Sound, served as the first saltwater test site of a tidal turbine system developed by a Laboratory and UW Department of Mechanical Engineering team. To generate predictable, reliable power in areas of strong tidal currents, the researchers designed a four-bladed cross-flow turbine with a 1 m^2 swept area integrated with a generator and supporting power electronics. "We moored R/V *Russell Davis Light* in the passage for one week this past spring, and used the gantry to lower the turbine rotor and generator into the currents that rip through at about 2 m/s," recalls Senior Engineer **CHRIS BASSETT**. "The system generated nearly 600 W at peak flow velocities and met all expectations during periods of sustained operation."

Also mounted to the *Light's* gantry were imaging sonars and stereo cameras to collect environmental observations related to knowledge gaps, including the risk of marine life collisions with the system. Bassett adds, "This environmental monitoring package operated continuously throughout the experiment, with the cameras capturing small fish, jellyfish, and krill near the rotor, but no large fish or other animals such as diving birds or seals, even though we knew they were in the area."

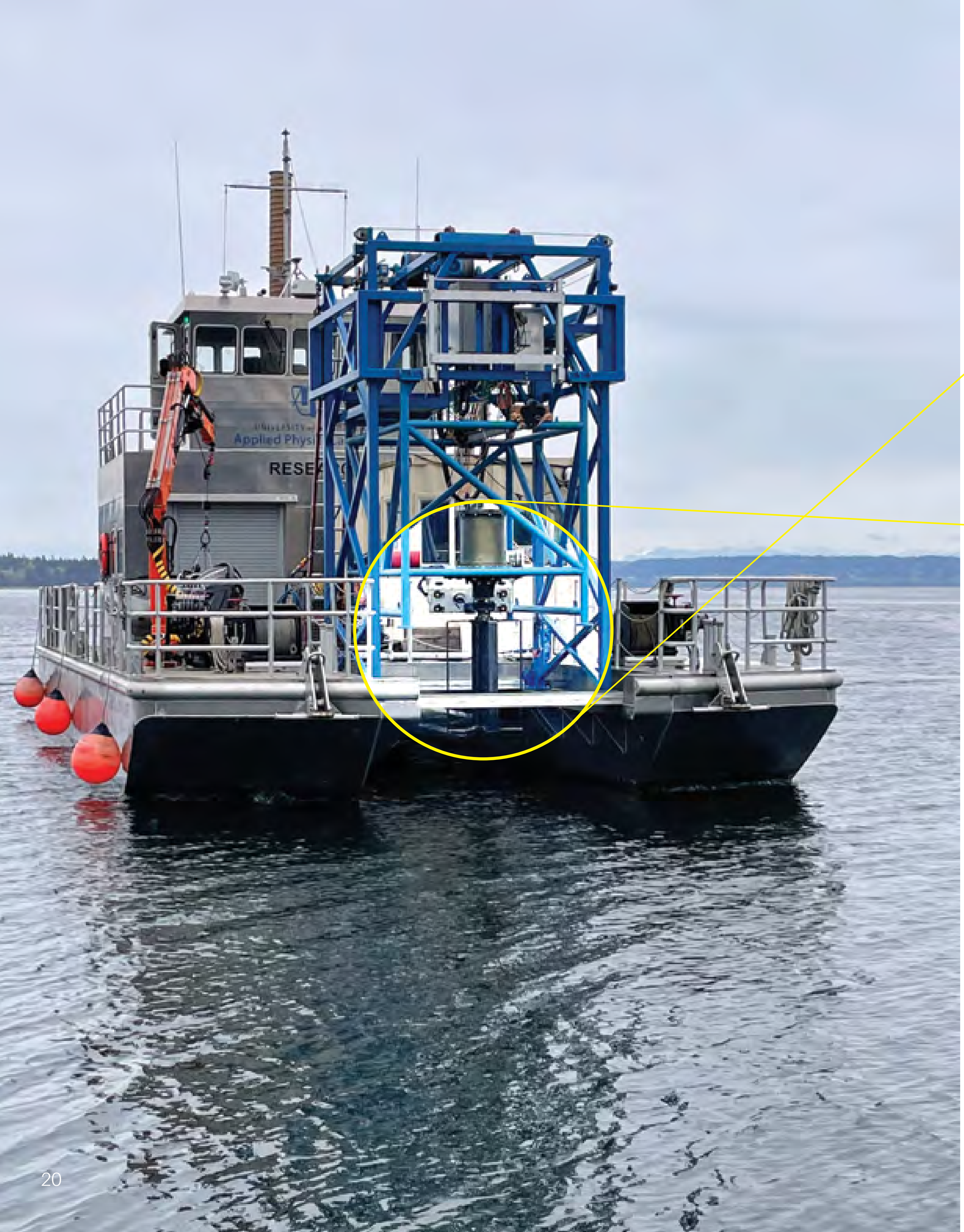
With the successful saltwater demonstration, the team is nearer its ultimate objective: to integrate the turbine power and monitoring systems to a four-legged bottom lander that can be deployed by a small vessel in coastal locations to power distributed sensor networks and recharge autonomous undersea vehicles, independent of cabled infrastructure or human intervention.

phased progress

Fundamental design and performance experiments with lab-scale turbines began in 2014 to determine the efficiency of various designs and to optimize turbine rotation speed, torque, and thrust loads. "By controlling the rotation rate of the blades relative to the free stream velocity of the water, we can maximize the power generated by the turbine," explains Bassett. Scaling up the best performing designs from lab experiments required material and mechanical modifications. Full-size prototypes with solid aluminum rotor blades experienced deflection under stress, so the APL-UW team partnered with a Washington company, Bieker Boats, to design stiff, carbon fiber blades fitted with titanium hinges that minimize stress concentration at connection points.

The test and evaluation of full-scale prototypes in the field has been supported by the purpose-built R/V *Russell Davis Light*. Under propulsion in Lake Washington the vessel simulates tidal currents. With the turbine rotor suspended and lowered by the vessel's gantry to a position below the bow, the team has been able to test the system and evaluate performance under controlled conditions. Early engineering tests were conducted with the generator mounted in the gantry above the water's surface with a long driveshaft connecting to the turbine below. To realize the short stack design goal of the turbine-lander, the team needed to integrate the full system — rotor, generator, power electronics — below the water line in a single package. A magnetic coupling between the rotor and driveshaft eliminates the need for a rotary seal and minimizes the chance of flooding the generator housing. Precise engineering of the drive train even required chilling some components in a cold lab freezer while others were heated in an industrial oven, then quickly assembling before they returned to their size at room temperature.

Adaptable Monitoring Package (AMP) development has progressed concurrently with marine energy capture and conversion devices. To detect, track, and classify all possible marine life and technology interactions requires the right mix of sensors and advanced software engineering. Onboard data processing capability and smart self-controls ensure that AMP sensors work together. For example, hydrophones can trigger sonar and optical imagers



and lights to capture rare events of interest, all while limiting the burden of data storage. Industry partner MarineSitu, spun off from the environmental monitoring technology development, continues to provide project support while moving toward commercialization of AMP-style systems. In various configurations, AMPs have been powered by a cable from shore, R/V *Light* itself, onboard batteries, and by an ocean wave energy converter during a six-month demonstration in 2019.

For the saltwater tests this past spring the turbine rotor and power takeoff were configured as in the final turbine-lander design, except upside down. The compact design will keep the lander's center of gravity low while at rest on the seafloor, making it less likely to tip over when tidal forces push against the turbine rotor. "We've collected volumes of engineering data during tests to characterize the turbine and power takeoff systems aboard the *Light*," remarks Bassett. "Despite some potential for improvement, the system is well designed for power extraction under a broad range of operational constraints." Under heavy loads in Agate Passage the system performed with no signs of mechanical fatigue, corrosion, or water ingress to the system's bearing pack, and the team verified that all components, including controls and data acquisition, sustained expected operation over extended periods.

turbine-lander at-sea demonstration

With environmental permitting approvals secured, an extended turbine-lander deployment is scheduled to begin in late 2022 in Sequim Bay offshore the Pacific Northwest National Laboratory Marine and Coastal Research Lab. The bay is connected to the Strait of Juan de Fuca by a 250-m wide channel, where the energetic tidal currents should exceed 2 m/s. Given the amount of prior characterization for the system, the team anticipates a successful multimonth demonstration. Over the period, an AMP integrated with the lander frame will operate continuously to document interactions between animals and the tidal turbine, because collision with the rotors remains a grave concern. In addition, measurements by the AMP's hydrophones and drifters will help to characterize the turbine's acoustic footprint during typical operations.

Test assembly by Mechanical Engineer **HARLIN WOOD** (l) and **BASSETT** (r) of turbine-lander components at APL-UW prior to deployment in Sequim Bay.

The Indian Ocean monsoon is the most striking and intense seasonal weather cycle on Earth and affects the livelihoods of more than one billion people living in Indian Ocean rim nations. Since 2014 the Office of Naval Research has funded a series of initiatives to bring together scientists and oceanographic research infrastructure from a total of 20 Indian, Sri Lankan, and U.S. institutions to understand more fully the ocean's role in monsoon onset and variability through observational and modeling process studies.

Laboratory oceanographers met with their Indian collaborators this summer to begin research cruise planning for upcoming field seasons. The COVID-19 pandemic imposed travel restrictions and logistics challenges that suspended the partners' productive, long-standing research initiatives focused on the northern Indian Ocean and Bay of Bengal. Resuming in-person collaboration, Senior Principal Oceanographers **ERIC D'ASARO** and **CRAIG LEE** traveled to the Indian National Centre for Ocean Information Services in Hyderabad to plan coordinated experiments with Indian and U.S. research vessels.

For APL-UW researchers, one area of focus in these collaborative efforts has been to measure the physical processes controlling upper ocean stratification in the Bay of Bengal. Existing coupled ocean–atmosphere models for the region predicted the summer monsoon poorly. A vast amount of fresh water is dumped into the Bay of Bengal, directly as rainfall and from river inflow, creating a strongly stratified, thin surface layer. It is as if the ocean itself is very shallow, intensifying the air–sea coupling. With models predicting ocean surface temperatures too cool and mixed layers too deep, the team sought higher vertical and horizontal resolution measurements focused on the near surface.

Office of Naval Research Departmental Research Initiatives

ASIRI
Air–Sea Interactions in the Northern Indian Ocean

MISO-BoB
Monsoon Intra-Seasonal Oscillation in the Tropical Indian Ocean and Bay of Bengal

ASTRAL
The Arabian Sea Transition Layer: Exchange Across the Air-Sea Interface

cooperative oceanography + knowledge sharing

During a multiyear collaborative research effort, with several multimonth cruises every year and long-term mooring, drifter, float, and glider deployments, an unprecedented oceanographic and atmospheric data set has been generated. Upper ocean structure, circulation, and air–sea interactions were resolved spatially from the basin to the microscale. With these observations demonstrating a larger role for the ocean in controlling the intraseasonal active/break periods of monsoon rainfall, predictive models are being modified to include the ocean in more detail.

Another APL-UW contribution to the initiatives has been to establish and maintain Seaglider survey lines in partnership with Sri Lanka's National Aquatic Resources Research and Development Agency. Over the course of six years of repeat observations to the east and south of Sri Lanka, over 12,000 glider profiles have measured the complex and variable circulation patterns connecting the Bay of Bengal and Arabian Sea to each other and the rest of the Indian Ocean.

While the Bay of Bengal has an annual net freshwater surplus, the Arabian Sea has net evaporation and high-salinity input from the Red Sea and Persian Gulf, producing a salinity surplus. Communication between the two seas through boundary currents along the Sri Lankan coast modulates this imbalance. The multiyear Seaglider surveys have measured seasonal and interannual variability in the exchange and its structure, quantifying volume, heat, and freshwater fluxes. The partnership with Sri Lankan scientists, as well as political support, has ensured continuous access to the critical, nearshore regions through which the boundary currents pass.

Fresh water exported from the Bay of Bengal, mostly during the northeast (winter) monsoon, creates a low-salinity pool between the Maldives and India. Modulating upper ocean stratification, it forms a barrier layer and a warm surface lens under the intensifying solar heating of spring into summer. The resulting amplification of air–sea coupling has a role in the onset of the northeast (summer) monsoon. Collaborative process cruises planned for 2023 and beyond on Indian and U.S. research vessels are guided by several questions. How much Bay of Bengal water is transported and what is its temperature before and after transit? How much of that water is evaporated to contribute to monsoon rainfall? How are salinity minima and temperature maxima in the warm pool linked to monsoon intensity?

These ONR-funded initiatives have produced an important body of scientific literature and trained scores of early career ocean scientists and engineers. Methods in instrumentation, data analysis, modeling, and synthesis have been entrained during joint cruises, summer schools, and workshops. This cadre of young scientists is deploying the latest physical oceanographic equipment, methods, and analyses to produce innovative experimental science focused on the tropical Indian Ocean.

l to r: **D'ASARO**, J. Sree Lekha (postdoctoral researcher at NOAA Pacific Marine Environmental Laboratory), **CHAUDHURI**, and Professor Debasis Sengupta (IISc, Bangalore)

In summer 2022 **DIVYA PANICKER** defended her Ph.D. thesis, *Cetaceans and Soundscapes in the Lakshadweep Islands, Northern Indian Ocean*, at the UW School of Oceanography. Panicker first met her thesis advisor Kate Stafford (now at Oregon State University) when Stafford taught a short course on bio-acoustics in 2014 at the Indian National Center for Biological Sciences, Bangalore.

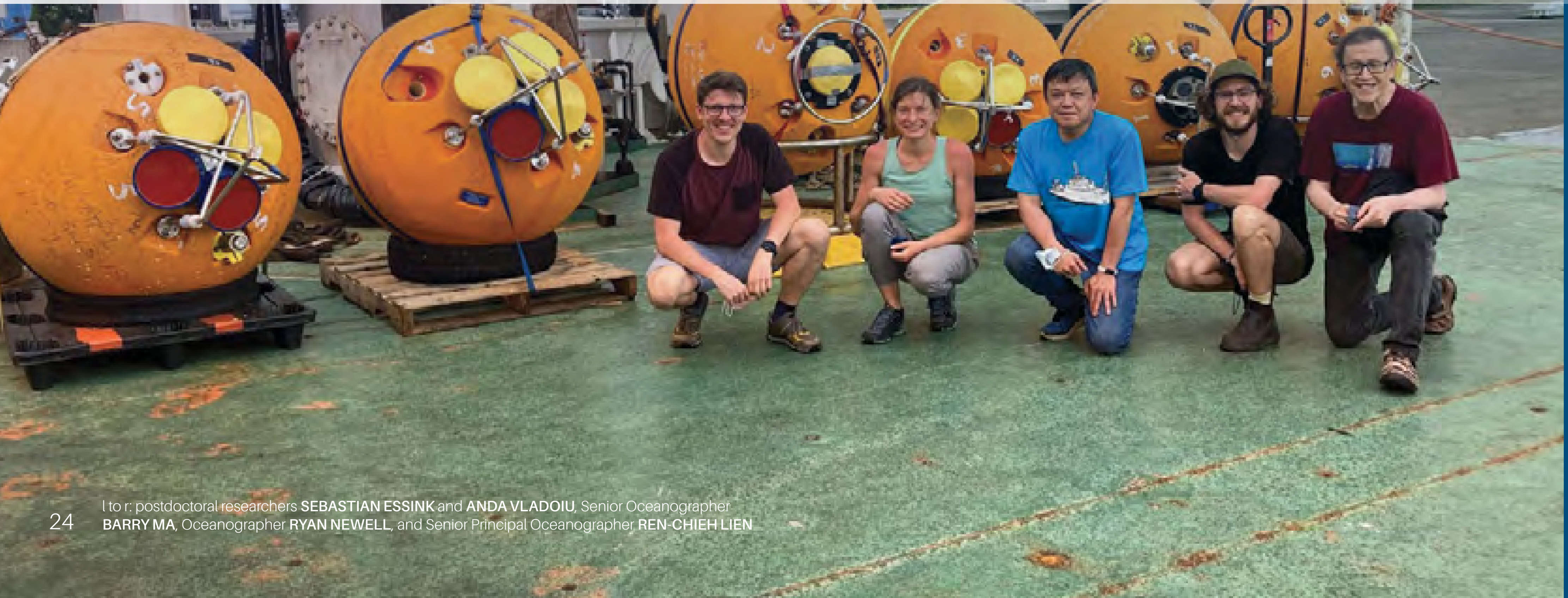
DIPANJAN CHAUDHURI earned a Ph.D. in climate science from the Indian Institute of Science, Bangalore in 2020 and is now a postdoctoral scholar at APL-UW advised by D'Asaro. In a recent paper, Chaudhuri analyzes data collected during 2014–2017 in the Bay of Bengal. He reports that extreme river inflow creates highly stratified, low-salinity pools that trap the momentum of monsoon winds near the surface and prevent wind-induced deepening of the mixed layer.

APL-UW scientists teach, advise, and mentor scores of students across the academic spectrum of our world-class research university every year: undergraduate and graduate students pursuing degrees in over a dozen disciplines, postdoctoral scholars whose career interests align with the Laboratory's areas of expertise, and early career investigators launching their independent research careers.

Over 40 Laboratory scientists hold faculty appointments in UW academic departments, principally in the College of Engineering and College of the Environment. Students pursuing UW degrees are entrained into their advisors' sponsored research projects, where they gain applied research experiences beyond the classroom, and build professional support networks.

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

next generation of scientists + engineers



l to r: postdoctoral researchers **SEBASTIAN ESSINK** and **ANDA VLADOIU**, Senior Oceanographer **BARRY MA**, Oceanographer **RYAN NEWELL**, and Senior Principal Oceanographer **REN-CHIEH LIEN**

graduate students, degrees earned, thesis titles, and apl-uw advisors

Taryn Black, Earth + Space Sciences, Ph.D., 2022
Investigations of Glacier Terminus Changes on Weekly to Decadal Time Scales
Ian Joughin

Samuel Brenner, Oceanography, Ph.D., 2022
The Role of Sea Ice in Atmosphere–Ocean Momentum Transfer
Luc Rainville + Jim Thomson

Robin Clancy, Atmospheric Sciences, Ph.D., 2022
Asymmetric Patterns in the Atmosphere and Sea Ice During Polar Cyclones and Their Changes Under Global Warming
Cecilia Bitz (Atmos. Sci.) + Rebecca Woodgate

Jessica Hale, Aquatic + Fishery Sciences, Ph.D., 2022
Foraging Ecology and Population Dynamics of Northern Sea Otters (Enhydra lutris kenyoni) in Washington State
Kristin Laidre

Suneil Iyer, Oceanography, Ph.D., 2022
Ocean–Atmosphere Feedbacks in Two Tropical Atmospheric Regimes: The Intertropical Convergence Zone and the Trade Winds
Kyla Drushka

Robert Levine, Oceanography, Ph.D., 2021
Climate-Driven Shifts in Abundance, Distribution, and Composition of the Pelagic Fish Community in a Rapidly Changing Pacific Arctic
Rebecca Woodgate

Lauren O'Neil, Earth + Space Sciences, Ph.D., 2022
Micro-X-Ray Fluorescence Mapping Data Analysis and Interpretation
Tim Elam

Divya Panicker, Oceanography, Ph.D., 2022
Cetaceans and Soundscapes in the Lakshadweep Islands, Northern Indian Ocean
Kate Stafford

EJ Rainville, Civil + Environmental Engineering, M.S., 2022
Measurements of Nearshore Waves Through Coherent Arrays of Small-Scale, Free-Drifting Wave Buoys
Jim Thomson

Curtis Rusch, Mechanical Engineering, Ph.D., 2021
Scaling of Point Absorber Wave Energy Converter Hydrodynamics
Brian Polagye (Mech. Eng.) + Chris Chickadel

design, deploy, analyze data

The small, inexpensive ocean drifter called microSWIFT, developed in Senior Principal Oceanographer Jim Thomson's lab, is central to the research programs of two civil and environmental engineering graduate students. "I wanted to get into oceanographic instrument development," recalls **EJ RAINVILLE**. "Jim sent me the description of a funded project to measure nearshore waves with coherent arrays of small, free-drifting buoys." **JACOB DAVIS** joined the lab at about the same time, adding, "They were near the end of the hardware phase, so I jumped in to develop software to process raw microSWIFT data."

In late 2021 the investigative team tossed, dropped, or launched 10 to 50 microSWIFTs at a time into the waves generated by seasonal storms offshore the Army Corps of Engineers Field Research Facility in Duck, North Carolina. And then in September 2022, as Hurricane Ian moved into the eastern Gulf of Mexico, Jake flew aboard a P-3 operated by the Navy's Scientific Development Squadron to seed the sea surface with five microSWIFTs and other drifters ahead of Ian's forecasted advance toward the Florida coast.

microSWIFT is a simplified and miniaturized version of the Surface Wave Instrument Float with Tracking (SWIFT) — now a mature technology developed by Thomson's lab to measure waves, wind, and turbulence at the ocean surface. The comparative low cost and portability of the tiny version allows deployment in large arrays to capture the rich variability of storm-induced ocean waves. EJ's and Jacob's projects are using the unique data sets to validate, compare, and improve simulations of wave field properties and forecasting models for coastal communities.

"Building the original and microSWIFT buoys required professional engineering, but also provides a great opportunity to get students involved," notes Thomson. "By contributing to hardware design and testing, and software engineering, the students build intuition about data quality and analysis methods, ultimately producing better science."

l to r: **THOMSON**, **RAINVILLE**, Engineer **EMILY ISELEY**, **DAVIS**, and Senior Engineer **MORTEZA DERAKHTI**

Since the SEED program's founding nearly a decade ago, postdoctoral scholars showing outstanding potential to establish independent research careers have been supported by two-year fellowships. Scholars have research goals aligned with Laboratory areas of interest and receive expert mentoring from APL-UW principal investigators. SEED fellows make significant contributions to the Laboratory's success and often become long-term additions to our science and engineering staff.

science + engineering enrichment + development

LAUR FERRIS arrived at APL-UW in spring 2022 with a clear vision of the research activities to pursue with SEED fellowship support. Ferris is a NORSE investigator (Northern Ocean Rapid Surface Evolution), having joined the ONR-funded initiative with Ph.D. advisor and NORSE co-investigator Donglai Gong at the Virginia Institute of Marine Science.

During doctoral studies, Ferris focused on measurements of near-surface turbulence in the highly energetic Southern Ocean using a unique, 6-week, 800-km microstructure survey collected by an autonomous glider. Ferris's results challenge some long-held assumptions: 'standard approximations' for strongly forced seas estimate 10 times too much or 10 times too little turbulence in different parts of the surface boundary layer. Ferris is applying her Ph.D. research experience to NORSE by coordinating the efforts of two groups — Gong's and Principal Engineer Justin Shapiro's — both running long-term glider surveys to observe the physical processes generating turbulence and altering ocean structure during the winter storm season in the ice-free Nordic seas. Here, warm, saline waters of the Norwegian Atlantic Current collide with the cooler and fresher waters of the Arctic, stirring and stretching into small fronts that evolve rapidly.

Ferris's science objective for NORSE is to place the glider-based turbulence data in the context of hydrographic and atmospheric measurements of the integrated program. This aligns with an overall research vision: "I'm seeking to untangle turbulence generating dynamics that are most influential to predicting ocean structure in a theater of extreme forcing, so that they can be better represented in operational ocean models. Most of those were developed based on available observations in quiescent oceans."

postdocs lead international experiments

Aboard a Taiwanese research vessel and collaborating with an international team of oceanographers, postdoctoral researchers **ANDA VLADOIU** and **SEBASTIAN ESSINK** led efforts in June to measure turbulent, billowing structures in the Kuroshio Current east of Taiwan. Here, the Kuroshio is forced over the rough topography of seamounts, which interrupt and roll up the flow into billows that extend for several kilometers in a turbulent wake.

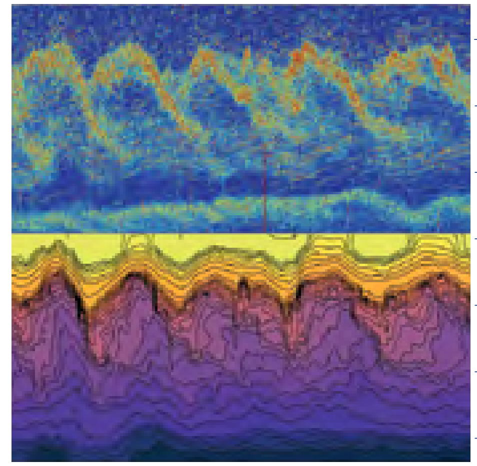
Vladoiu and Essink proposed the project, *Kelvin–Helmholtz Instabilities at a Kuroshio Seamount*, to the National Science Foundation "... and were awarded funding upon their first submission," notes advisor and Senior Principal Oceanographer Ren-Chieh Lien. "It's the first major award won by postdocs as principal investigators in our APL-UW department," he adds.

Extending over multiple cruises and seasons, their research seeks to observe the generation of the flow instabilities on a seamount summit, the turbulence and mixing as billows move downstream, and water property transformation. Essink explains the challenge, saying, “In the ocean these features have so far only been measured in estuaries and inlets, where they contribute significantly to mixing, but are only 3–5 m tall. Here in the Kuroshio, however, we know from previous shipboard echosounder observations that trains of billows have a horizontal scale of 200 m and are up to 100 m tall.”

Their observing strategy relies on a 400-m-long towed CTD chain. “It combines 57 closely spaced CTD sensors, yielding 1–2-m vertical resolution over the targeted depth range of the billows,” explains Vladoiu. “We are one of only a few groups in the world to use towed chains and it’s certainly the first time that oceanic Kelvin–Helmholtz billow properties have been measured with such high resolution and in 3D.” The postdocs and Lien joined investigators from three Taiwanese institutions aboard the research vessels ***New Ocean Researcher I*** and ***III***. Together, they also deployed six temporary moorings near the seamounts and downstream equipped to measure flow velocity, tides, small-scale internal waves, and the billows directly.

The cruise was a complete success. The collaborative team found and measured large, overturning instabilities, running 15 towed CTD chain spatial surveys overlapping the extent of moored observations and collecting deep towed chain hydrographic time series at dozens of stations. “With this beautiful data set, we are tackling the first task of understanding how these instabilities are generated,” adds Vladoiu.

Besides their capability to write a successful science proposal, advisor Lien credits Vladoiu and Essink with planning successful at-sea experiments and developing partnerships with researchers at National Taiwan University and National Cheng Kung University, who were critical to the experiment’s success. Vessel availability, science and engineering crew support, and the permission to operate within Taiwan’s territorial waters made observations of these unique ocean phenomena possible.

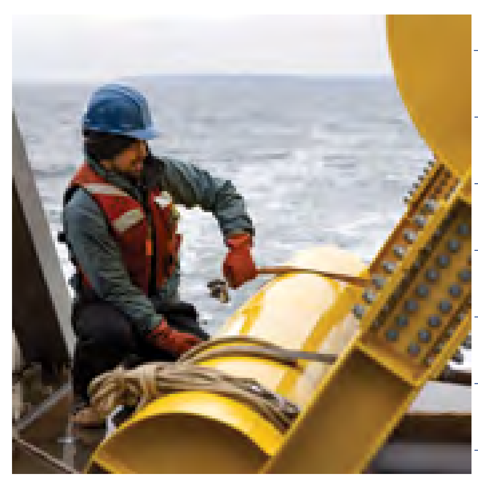


coupling robotic oceanographic platforms with marine renewable energy technologies

Aboard R/V *Robertson* on Puget Sound this past spring, **CURTIS RUSCH** passed a significant milestone in his career since earning a Ph.D. in mechanical engineering at the University of Washington. He and the multidisciplinary crew demonstrated an integrated system to operate, dock, and wirelessly recharge an uncrewed underwater vehicle (UUV) with energy captured from ocean waves and converted to electricity.

“As an undergrad I started working on all kinds of wave energy projects at the Laboratory,” recalls Rusch. Now, as a postdoctoral researcher, he adds, “It’s exciting to be part of a project where we are applying wave energy to an oceanographic observing platform as an integrated unit.” Funded by the Naval Facilities Engineering Systems Command, the project’s goal is to evaluate and demonstrate a wave energy converter that can produce persistent, modest amounts of electricity to sustain oceanographic instruments and sensors beyond their standard battery lives in remote and forward-deployed environments.

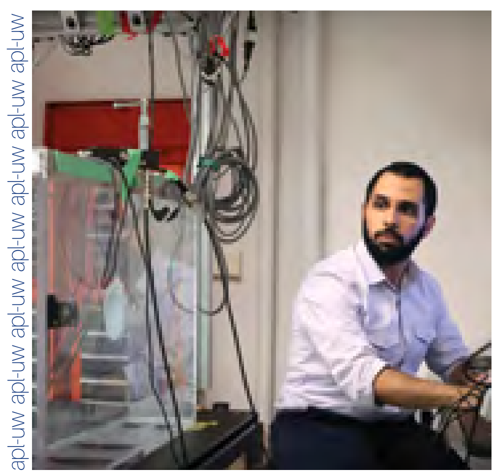
Rusch’s area of expertise and subject of his dissertation is point absorber wave energy converter (WEC) hydrodynamics. These systems, like the one tested in Puget Sound, consist of floating bodies at the surface connected to a submerged reactive body, a heave plate, and a stable core containing the power takeoff system. As the core reacts against the heave plate in ocean waves, the motion between the floating bodies is converted to electricity.



Collaborative efforts to optimize heave plate design were key to project success. Storage batteries and the UUV’s docking station were mounted on the plate, a wireless power transfer system was installed, and the system’s power output had to be balanced with the need to minimize heave plate motion that could impede the UUV’s docking maneuvers.

“The success of these tests relied on the synthesis of several cutting-edge technologies, collaboration among electrical, mechanical and ocean engineers, as well as partnerships with industry professionals,” says Rusch. “These accomplishments and data collected on Puget Sound will prepare us for longer deployments of power-intensive oceanographic systems free of human intervention.”

entraining scientists and engineers into health care research



Postdoctoral scholar **MOHAMED GHANEM** received this summer one of the most prestigious awards an early career independent researcher can win — a K grant from the National Institutes of Health. This NIH grant program provides research support and career development opportunities to investigators with quantitative science and engineering backgrounds, and helps steer their expertise toward NIH-relevant research focused on questions of human health and disease.

Ghanem joined the Center for Industrial + Medical Ultrasound and Mike Bailey’s lab as a graduate student, completing doctoral studies on acoustic manipulation of macroscopic objects. His work with a custom 256-element transducer to create acoustic cages that can grab and hold objects has been one component of the lab’s efforts to develop an ultrasonic therapy system to treat kidney stones noninvasively. He was awarded an APL-UW SEED fellowship in 2020, which afforded time to continue development of the ‘acoustic forceps’ technology, as well as mentoring and collaborative opportunities.

During the fellowship, Ghanem completed theoretical studies of complex beam forming and acoustic scattering from irregularly shaped objects, and has developed methods to use feedback from objects to correct beam shape and steering precision.

The team in Bailey’s lab has demonstrated the ability to levitate, hold, and move glass beads over short, precise distances in a porcine bladder. With NIH support, Ghanem will advance the technology and methods to move actual stones of various sizes, shapes, and compositions over clinically relevant distances in real kidneys with ‘acoustic forceps’.

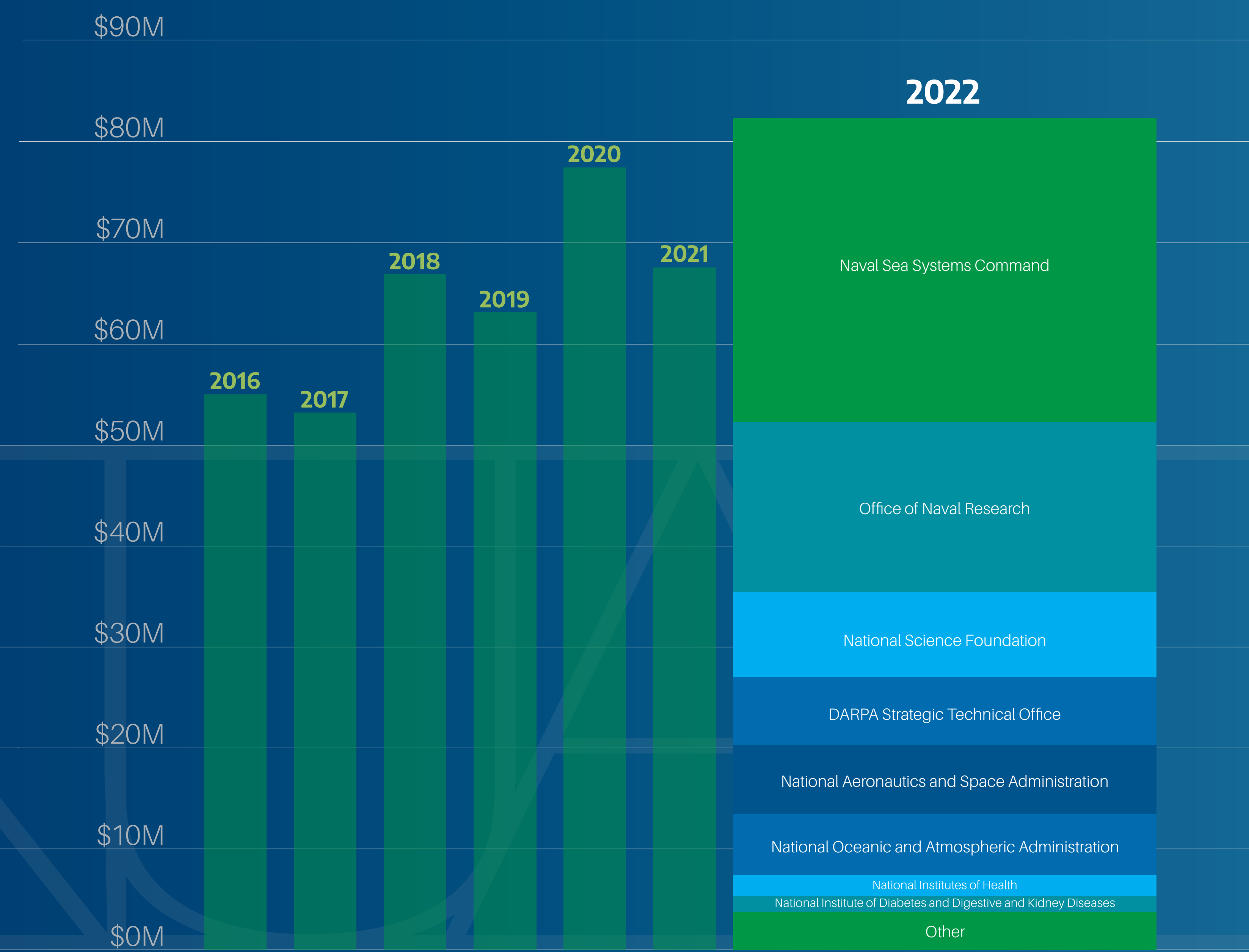
The Applied Physics Laboratory experienced record growth in research awards during FY22 with a total of $82.5M. This represents an increase of over $15M from FY21 and exceeds the record total reported in FY20. Growth of this magnitude demonstrates the Laboratory's continued ability to engage in research despite the many challenges posed by the changing landscape of safety regulations, environmental considerations, and funding priorities.

Federal agencies continue to be the top sponsors of research at APL-UW, accounting for 95% of all funding. In FY22, research funded by tasks executed under the Naval Sea Systems Command contract increased by 64%, totaling $29.7M and representing 36% of all funds received for the year. In addition to NAVSEA, support from other federal agencies grew significantly year over year, including the National Science Foundation, Defense Advanced Research Projects Agency, and the National Institutes of Health.

The record setting award level resulted in an increase in the amount of revenue generated to support ongoing operations at the Laboratory, allowing us to continue investing in people and infrastructure and ensuring that we continue to lead in scientific discovery and technology innovation. These investments: providing the resources to grow the expertise of the Laboratory's staff; promoting a culture of diversity, inclusion, and belonging; supporting postdoctoral scholars in their continued professional development; and investing in facilities, security, and technology infrastructure, all ensure the Laboratory's ability to respond quickly to the needs and changing priorities of our sponsors and researchers.

financial health

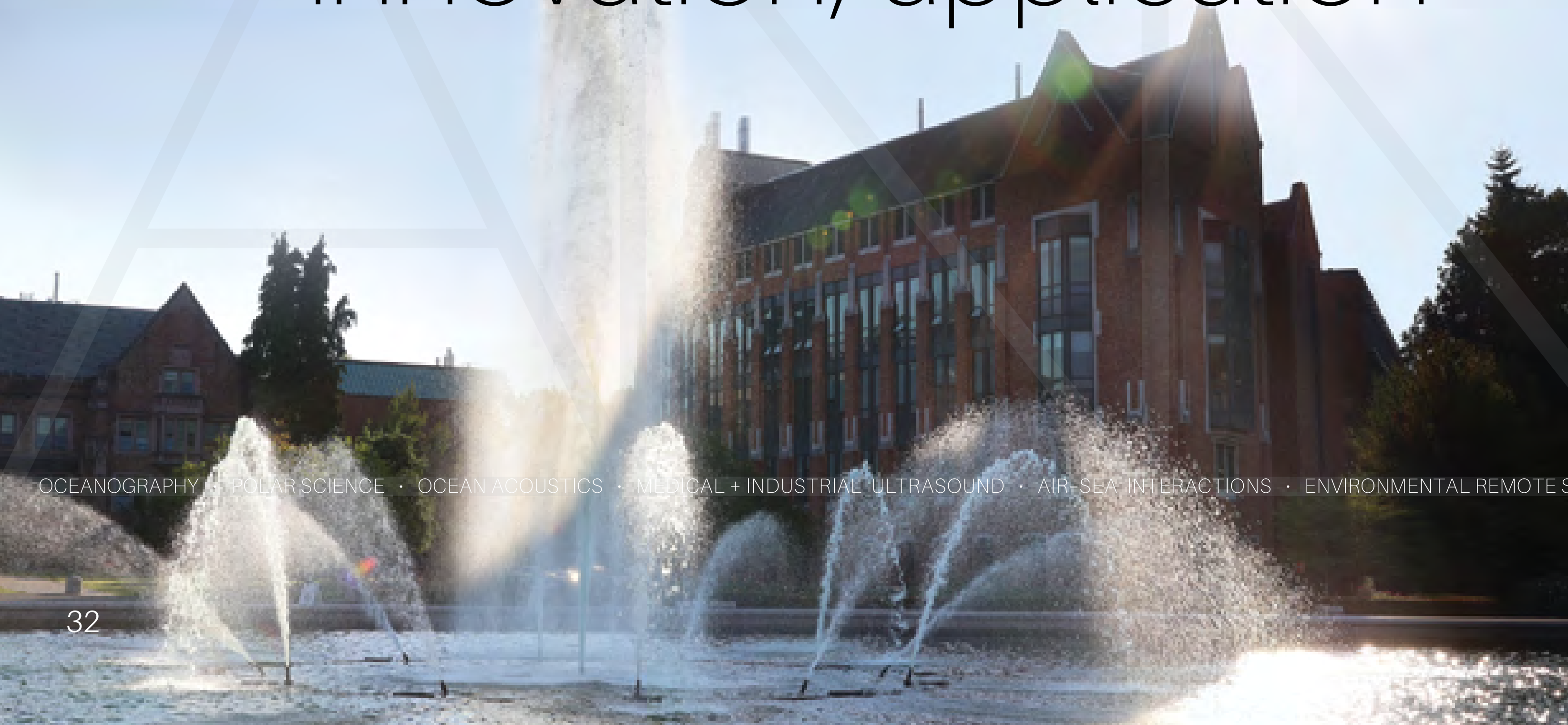
Work continues on critical infrastructure in FY23. Prorated direct cost and discretionary funds have been set aside to complete the dock facility replacement project. The University of Washington's transition to Workday Financials represents a long-term opportunity to increase efficiency but a short-term challenge to ramp up staff and technology resources to ensure minimal impact to the research enterprise during the upgrade. These priorities to enhance support throughout the organization are especially important because we expect continuing growth in research activities.



The Applied Physics Laboratory's parent institution, the University of Washington, is one of the world's preeminent universities, linking academic excellence to cutting-edge research. The UW receives more sponsored grant and contract research funding ($1.67B last year) than any other public university in the nation.

The Laboratory's success in meeting the needs of our research sponsors with science-based knowledge and applied technologies is enhanced by our deep integration into the UW enterprise: research excellence, student opportunity and achievement, the imperative to innovate, and our public promise to our region, nation, and world.

scholarship, discovery, innovation, application



leadership

laboratory

KEVIN WILLIAMS	Executive Director
WARREN FOX	Deputy Executive Director
. . .	
CHRIS CHICKADEL	Chair, Air–Sea Interaction and Remote Sensing
JAMES GIRTON	Chair, Ocean Physics
MIKE HARRINGTON	Director, Electronic and Photonic Systems
TODD HEFNER	Chair, Acoustics
DAVID KROUT	Director, Environmental and Information Systems
BONNIE LIGHT	Chair, Polar Science
THOMAS MATULA	Director, Industrial and Medical Ultrasound
NICK MICHEL-HART	Head, Ocean Engineering
. . .	
BEN ADAMS	Facility Security Officer
MARIA CARD	Director, Human Resources
DIAN GAY	Director, Resources and Facilities
AUTUMN SALAZAR	Director, Business and Finance

university

ANA MARI CAUCE
President

MARK RICHARDS
Provost

MARI OSTENDORF
Vice Provost for Research

The Applied Physics Laboratory - University of Washington
1013 NE 40th Street, Seattle, WA 98105-6698
t 206.543.1300 | f 206.543.6785 | switchbd@apl.uw.edu

apl-uw annual report creative team: Brian Rasmussen and Maia LeDoux

OCEANOGRAPHY · POLAR SCIENCE · OCEAN ACOUSTICS · MEDICAL + INDUSTRIAL ULTRASOUND · AIR-SEA INTERACTIONS · ENVIRONMENTAL REMOTE SENSING · ELECTRONIC SYSTEMS · OCEAN ENGINEERING · CLIMATE SCIENCE · AUTONOMOUS SYSTEMS · MARINE ENERGY · SIGNAL PROCESSING apl.uw.edu