

NAVAL SCIENCE AND TECHNOLOGY FUTURE FORCE™

VOL. 6, NO. 1, 2019

DISCOVERING THE SEA AT
WOODS HOLE AND SCRIPPS

POWERING INSTRUMENTS
WITH WAVE ENERGY

MAPPING THE OCEAN
FOR SOUND

OCEAN SCIENCE AND TECHNOLOGY





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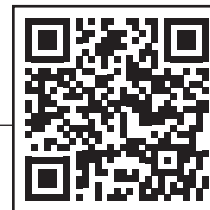
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A Revolutionary Relationship: The Navy and Woods Hole

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Future Force is a professional magazine of the naval science and technology community. Published quarterly by the Office of Naval Research, its purpose is to inform readers about basic and applied research and advanced technology development efforts funded by the Department of the Navy. The mission of this publication is to enhance awareness of the decisive naval capabilities that are being discovered, developed, and demonstrated by scientists and engineers for the Navy, Marine Corps, and nation.

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In 1946 President Harry S. Truman approved legislation establishing the Office of Naval Research (ONR), charging this new organization to "plan, foster and encourage scientific research in recognition of its paramount importance as related to the maintenance of future naval power, and the preservation of national security." Note the tone these carefully chosen words "foster" and "encourage" evoke. It was true then, as it is now, that the best results come from tapping into the creativity and passion of the research community—not by direction of what should be done, but through a spirit of partnership and shared objectives.

Within this issue are examples of that partnership and some of the tremendous achievements of two of our nation's premier oceanographic institutions. The Scripps Institution of Oceanography, now part of the University of California, San Diego, and the Woods Hole Oceanographic Institution have histories of critical support for the United States Navy. Answering not only to the stated needs of the fleet, but pushing forward novel tools and techniques that enabled major leaps in understanding the ocean environment. Many of the scientists and engineers involved were not only leaders of the US oceanography community, but had keen insight into our Navy's challenges and objectives.

In the years after the fall of the Soviet Union, the Navy's existential focus on undersea warfare diminished greatly. ONR's investment in the academic research community atrophied. We are now entering into another era in which our ability to maintain undersea superiority is both challenged and critical to national security. To re-establish the critical ties between the Navy and the academic community that paid such rich dividends previously, then Chief of Naval Operations Admiral John Richardson initiated Task Force Ocean (TFO). Executed by the chief of naval research and under direction of the oceanographer of the Navy, TFO has three primary thrusts: to plan, foster, and encourage scientific research within the academic community, industry, and Navy labs and centers related to undersea warfare; to facilitate the research community's appreciation of the naval operational environment by exposing researchers to Navy operations and training; and to build connections across the Naval Research Enterprise, fleet operators, and acquisition community through topical tactical oceanography symposia.

As ONR's academic research ties so richly supported the Navy then, we are re-committed to the support of our future force.

Dr. Drake is the head of the Ocean Battlespace Sensing and Expeditionary Access department at the Office of Naval Research.



CVN-72

OCEAN SCIENCE AND TECHNOLOGY



HOW WE GOT HERE PROJECT NOBSKA

By Colin E. Babb

USS *Tullibee* (SSN 597), shortly after commissioning in 1960.

OCEAN SCIENCE WAS STILL FINDING ITS FEET WHEN, MORE THAN 60 YEARS AGO, A SUMMER MEETING IN CAPE COD PLACED OCEANOGRAPHY AT CENTER STAGE FOR THE SAKE OF NATIONAL DEFENSE, AND HELPED PAVE THE WAY FOR MODERN UNDERSEA WARFARE.

Despite the fact that more than 70 percent of the Earth's surface is covered by water, the study of what lay beneath the ocean surface as a rigorous scientific discipline is a relatively recent development. Until the 20th century, rudimentary diving bells used by wreck salvagers offered the only way to view the oceans' depths; lead lines, hooks, and nets provided the only way to scoop or snag its mysterious inhabitants from below. It was only in 1930 that William Beebe and Otis Barton descended in the first truly deep-sea dive in their bathysphere, to around 1,400 feet. (It was also in this same year that the first doctorate in oceanography was awarded, at Scripps Institution of Oceanography.) World War II—and especially the challenge of fighting U-boats in one ocean, and supporting a massive submarine campaign in another—changed all this. The war put oceanographers, literally and figuratively, on the map.

More than a decade later, in the summer of 1956, scores of oceanographers, scientists, engineers, naval officers, and others met in Woods Hole, Massachusetts, for several months to address a pressing problem: How would the US Navy respond to the looming threat of Soviet nuclear-powered submarines? Called "Project Nobska" (after the lighthouse at the entrance to the harbor at Woods Hole), this summer study was a landmark not only in the long-term effects it had on the development of antisubmarine warfare, submarine design, and nuclear weapons at sea, but also in the way it brought ocean scientists into even closer collaboration with the government, military, and industry.

The urgency of Nobska's task was propelled not so much by firm knowledge of Soviet advances, but the presumption that the Soviets would soon emulate the latest American achievements: the construction of the first nuclear-

powered submarine, USS *Nautilus* (SSN 571); and the building of the revolutionary research submarine, USS *Albacore* (AGSS 569), the first boat to employ a "teardrop" hull to maximize underwater speed. The chief of naval operations, Adm. Arleigh Burke, wanted to take advantage of several decades of advances in ocean science to address the larger implications, opportunities, and challenges posed by these vessels. The Office of Naval Research paid for the expenses of the gathering, which began on 18 June 1956.

Participants included Nobel laureate Isidor Isaac Rabi and physicist Edward Teller, both of whom had worked on the Manhattan Project. Also attending was Paul Nitze, who had been principal author of NSC 68, the seminal policy document that advocated for the military expansion of the United States as an answer to Communism. He would later serve

as secretary of the navy. Among the notable oceanographers at Nobska were Fred Spiess from the Scripps Institution of Oceanography and Allyn Vine from Woods Hole. Organizational affiliations ranged from Bell Telephone to Johns Hopkins University to more than a dozen navy offices, bureaus, and other laboratories. Chaired by Woods Hole director Columbus O'Donnell Iselin, and brought together nominally under the direction of the National Academy of Science's committee on undersea warfare, Nobska's purview was broad.

Subgroups included technical topics such as weapon effects and limitations, propulsion, navigation and communication, detection, and missiles and torpedoes. Other groups investigated protection of ships at sea, strategic use of the undersea, containment of submarines and the

defense of the continental United States, and implications of political trends on undersea warfare. The 73 participants spent several weeks receiving numerous briefings as well as getting some time at sea aboard destroyers. By the end of the summer, Project Nobska had produced a two-volume report that included 51 recommendations on everything from the continued development of active and passive sonar, the size of nuclear submarines, the future of antisubmarine warfare, the use of tactical nuclear weapons in naval warfare, the possibility of basing strategic weapons at sea, and a host of other proposals for exploiting the newest discoveries of oceanography for national security.

Project Nobska and its legacy were not without critics. In 1966, in the aftermath of a new gathering called "Nobska II" that focused on

ocean surveillance (and included some of the same participants as in 1956), one observer argued that the original meeting's implementation had failed to meet expectations. "Nobska came out like this. Captain Carmichael, then in OP-03C [Fleet Operations and Readiness], took every recommendation, matched it up with the nearest operational requirement and said, 'See, we are doing something about this already, consequently we don't have to do anything more. These recommendations will not require new money.'" Similarly, some recommendations, such as for smaller submarines with reduced-sized reactors, were largely ignored by the bureau chiefs (and director

of naval reactors, Rear Adm. Hyman Rickover) as unreasonable tweaks to existing programs.

Perhaps the most important legacy of the summer study of 1956, however, ended up being its effect on its original cheerleader: Arleigh Burke. The arguments made by Teller for pursuing a smaller-yield warhead for strategic weapons convinced Burke to withdraw the Navy in the joint Jupiter missile program with the Army and to commit Navy resources to what would become the Polaris missile. In addition, Nobska's recommendations on pursuing innovations in both passive and active sonar led to later significant design changes in future US submarines that placed sonars in the bow and moved torpedo tubes amidships, allowing for larger, more powerful sonar systems. This resulted in a whole new direction for submarine design; the first example of this was USS *Tullibee* (SSN 597, launched in 1960).

After Nobska, the destinies of oceanographers and naval professionals would be inextricably linked—for better or worse. "Nobska offered oceanographers a chance for the greatest possible professional visibility," wrote historian Gary Weir. "It also set them on a path to more complete integration with other scientists, naval engineers, technical specialists, and leading naval officers by offering a greater opportunity than ever to influence national planning." After that pleasant summer in Cape Cod, the needs of ocean science and the needs of the navy would be difficult to pull apart. ✈

About the author:

Colin Babb is a support contractor serving as the historian for ONR and managing editor of *Future Force*.



Admiral Arleigh Burke, who became chief of naval operations in 1955, was the driving force behind Project Nobska.

A REVOLUTIONARY RELATIONSHIP: THE NAVY AND WOODS HOLE

By Warren Duffie Jr.



FAMOUS FOR ITS DISCOVERIES IN THE DEEP SEA—FROM *TITANIC* TO HYDROTHERMAL VENTS—WOODS HOLE HAS BEEN EXPLORING THE OCEANS SINCE 1930.

In 1944, the American submarine USS *Guitarro* (SS 363) prowled the South China Sea for Japanese vessels. Spotting a large ship convoy, *Guitarro*'s crew fired a volley of torpedoes and scored three hits on an unlucky target, shredding its bow and sinking it.

To avoid counterattack by an approaching Japanese escort destroyer, *Guitarro* dove several hundred feet. As the submarine descended, Sailors in its control room paid close attention to a device called a bathythermograph.

The device consisted of a small, torpedo-shaped instrument that attached to the outside hull and connected to a black box inside the submarine. The box contained a glass slide the size of an index card. An attached stylus traced a line across the slide, similar to an Etch-A-Sketch, indicating external temperature and depth changes.

The straight line suddenly curved sharply, a sign *Guitarro* crossed one of the ocean's thermocline layers—where water temperature shifted so dramatically that it deflected the probing pings of enemy sonar and enabled submarines to avoid detection. *Guitarro* shut off its engines and floated soundlessly.

Unsure of the submarine's location, the Japanese destroyer indiscriminately launched depth charges, hoping for a lucky hit. As explosions went off around *Guitarro*—their vibrations rattling the submarine—its crew stayed silent for what seemed like forever. When the overhead threat finally sailed away, *Guitarro*'s crew breathed easier and resumed stalking for prey.

A few months later, scientists at Woods Hole Oceanographic Institution (WHOI) in Massachusetts received a used bathythermograph slide from *Guitarro*. Like other US submarines, it returned the slides so oceanographers could create a database of undersea temperature and salinity records.

Crews often sent messages with the slides. Sailors from *Guitarro* wrote, "The engineering officer is happy to be able to forward this card because it means we were able to 'walk away'. . . following a successful attack on a heavy cruiser."

Another submarine composed a single sentence praising one of the WHOI scientists who invented the life-saving bathythermograph: “Thank God for Allyn Vine.”

“The bathythermograph saved many lives,” said Richard “Dick” Pittenger, who is WHOI’s special assistant for strategic planning and spent 37 years in the Navy, retiring as a rear admiral. “It’s perhaps the most important and successful Navy-Woods Hole collaboration of World War II.”

A Partnership of Science and National Security

The Guitarro episode exemplifies the value of the seven-decade partnership between WHOI and the US Navy—which revolutionized both naval warfare and the field of oceanography.

Nestled along one corner of scenic Cape Cod, WHOI is the world’s largest nonprofit ocean-science research institution. It formed in 1930 to study how the ocean interacts with the Earth—and foster greater understanding of the ocean’s role in the evolving global environment.

Because the ocean is the Navy’s primary operating environment, the service has a compelling interest in understanding this unforgiving, unpredictable battlescape.

“The Navy and Woods Hole have long partnered on the cutting edge of oceanographic platforms,” said Dr. Tom Drake, head of the Ocean Battlespace and Expeditionary Access Department at the Office of Naval Research (ONR), which sponsors scientific research for the Navy and Marine Corps. “This has been essential to the Navy’s ability to exploit the ocean environment to our advantage by learning about its various properties.”

Today, Navy funding accounts for approximately 10 percent of WHOI’s sponsored research budget. WHOI also maintains and operates two Navy-owned research vessels for use by the US scientific community, and the Navy-owned submersible *Alvin*—America’s deepest-diving, human-occupied research submarine.

Alvin is named for Dr. Allyn Vine, a WHOI engineer and geophysicist, who, in addition to his World War II bathythermograph work, pioneered deep-submergence research and technology. (See accompanying article about *Alvin* on page 14.)

“For decades, ONR and the Navy have offered the crown

jewel in ocean research funding,” said Mark Abbott, WHOI president and director. “They have supported high-risk science for various groundbreaking ideas and accelerated the discipline of oceanography—which, in turn, helped grow Woods Hole and give it a new focus on national security issues.”

Shining a Spotlight on Oceanography

At the turn of the 20th century, many naval officers doubted the tactical and strategic value of oceanography. While they saw the importance of understanding winds and ocean currents, they still considered accurate nautical charts and skilled seamanship the most vital weapons of sea-based combat.

World War I shattered that idea with the emergence of a terrifying new warfighting technology—the German U-boat.

In his book *An Ocean in Common*—which chronicles the relationship between American naval officers and scientists in developing oceanography as a respected scientific discipline—naval historian Gary Weir writes that this revolutionary submarine infused ocean warfare with a “potent third dimension that extended below the keel. The submersible presented a truly unusual strategic and tactical threat without conventional solution.”

The opening of the undersea battlespace drove a decades-long movement between the federal government, the Navy, academia and industry to study the physical, chemical, and geological makeup of the ocean—and harness this knowledge to give the United States a warfighting edge.

This effort gained steam in 1939, when World War II broke out in Europe. To marshal America’s scientific resources for probable entry into the global conflict, President Franklin D. Roosevelt’s administration created the National Defense Research Committee in 1940. The 10-year-old WHOI was among the research institutions called to service, and it saw its staff expand from 60 to more than 300, and its operating budget swell to over \$1 million (nearly \$18 million in today’s dollars).

WHOI’s first Navy-sponsored project targeted biofouling—the barnacles, seaweed, and other marine life that clings to ship hulls, slowing them and increasing fuel consumption. The institution’s research involved studying antifouling paints and making them deadlier to the sticky stowaways but less toxic to humans and aquatic life—consequently lowering the Navy’s fuel bill by 10 percent.

Other research included the use of underwater explosives to test how sound traveled underwater. This resulted in the discovery of the Sound Fixing and Range (SOFAR) channel—also called the Deep Sound Channel—a layer of water in the ocean that acts like a pipeline for efficiently transmitting low-frequency sound over vast distances.

In addition, researchers analyzed the effects of salinity and temperature on the transmission of underwater sound, and its application to submarine warfare. This led to perhaps WHOI's most important World War II innovation—the bathythermograph that protected submarines like *Guitarro*.

Preventing a Cold War, Exploring the Ocean

When World War II ended, WHOI scientists wondered about oceanography's future. Would scientific advances continue at present pace or would a world weary of war require less study of the seas? These concerns proved unfounded, since the direction and importance of oceanography had changed forever.

The establishment of ONR helped accelerate WHOI's prominence. ONR sponsors wide-ranging basic research and technology development, including ocean properties and processes. Weir writes in *An Ocean in Common* that through the creation of ONR, "the Navy established the most liberal, effective and flexible federal patronage agencies in history. With several ONR divisions supporting oceanography, the new discipline grew at an extraordinary rate multiplying both the scientific possibilities and . . . professional concerns."

Between 1946 and the end of the Cold War, the Navy sponsored diverse national security-related work conducted by WHOI. For example, 30 scientists traveled to Bikini Atoll in the Marshall Islands to perform before-and-after surveys of the test areas for atomic bombs. In 1956, WHOI hosted Project Nobska, which helped determine the next generation of undersea warfare (see "How We Got Here," on pg. 6).

WHOI also built on its SOFAR channel discovery from World War II, enabling the 1952 creation of the Navy's Sound Surveillance System (SOSUS)—which could detect submarines by their faint acoustic signals, via specialized microphones, called hydrophones, placed on the ocean floor. SOSUS and its increasingly advanced descendants allowed US forces to track and, if needed, engage Soviet submarines—a powerful deterrent to a shooting war.

While much of WHOI's Navy-sponsored research was classified, other aspects propelled oceanography into the public eye and ushered a golden age of exploration, including new fields of study.

Extensive work in physical oceanography led to better understanding of the Gulf Stream and North Atlantic Ocean. Acoustics allowed geophysicists to extend their knowledge of the structure of the Earth underneath the ocean. Bioacoustics studied the sounds made by marine animals and their effect on sonar operations. Interest in meteorology resulted in improved observations and insights into atmospheric physics and dynamics.

Such impressive scientific work stemmed from an improved ability to sail the ocean and study it firsthand. The catalyst? The federal government and academia collaborated to create a fleet of durable research vessels that could accommodate numerous scientists and pieces of scientific equipment, operate in bad weather and high seas, and collect large amounts of water and sediment samples.

The Navy currently owns six research vessels that are part of the US academic research fleet. Various universities and scientific organizations operate these ships under charter agreements with ONR.

WHOI operates two of them—R/V *Neil Armstrong* and R/V *Atlantis*. The ships are floating laboratories with sonar and ocean bottom-mapping equipment, heavy cranes and sample-collecting gear, diving and small boat-launching facilities, and meteorological sensors.

"We do a lot of physical oceanography aboard the ship," said Kent Sheasley, captain of *Neil Armstrong*. "We place different vehicles and sensors in the ocean to look at the water column and how things like climate and current mixing affect the underwater battlespace environment. We're grateful to the Navy for providing a ship that's so durable and sophisticated. It makes it easier to put delicate equipment into a not-so-delicate environment."

Naval Oceanography after the Cold War

The fall of the Berlin Wall in 1989 drastically shifted naval research priorities. It was no longer necessary to focus exclusively on the Soviet Union's large submarine force in the deep ocean. Within a few years, the first Gulf War—as well as new and renewed conflicts in places like the Middle East, eastern Europe and Taiwan—pushed the Navy's interest toward operations in shallow, often mined, coastal waters.

The focus evolved from “blue water” to “littoral” warfare.

While unforgiving, the cold, deep ocean is relatively stable and predictable. Coastal waters, on the other hand, churn with vastly different temperature and salinity levels—often mixing violently, like a giant washing machine. Tides, wind-driven currents, inflows from rivers, and changing air temperatures accelerate this aquatic agitation. If those elements aren’t enough, shipping noise, fishing activity, and reverberating seafloor topography that bounces sound in all directions make the littorals an acoustic nightmare, especially for operations such as mine detection.

To comprehend this challenging environment, the Navy sponsors diverse research in areas such as robotics (unmanned and autonomous underwater vehicles) and acoustics.

Gliders and REMUS

Dr. Robert Todd lifted a winged, four-foot, red-and-white robotic vehicle and pointed to a long, jagged crack on its top. He then picked up the object responsible for the damage—a triangular, serrated tooth.

“This robot was attacked by a shark along Cape Hatteras in North Carolina,” said Todd, a WHOI physical oceanographer. “However, the vehicle kept going and continued collecting underwater data while traveling to Massachusetts. It’s an example of durable, capable technology doing important work for the Navy.”

Todd performs ONR-sponsored research using gliders, which are sensor-laden, cylindrical unmanned vehicles that swim under water in a sawtooth pattern—up and down, up and down—for months at a time. Each glider measures seawater temperature, salinity and current velocity—and sends this data via satellite to WHOI by surfacing, rolling over and lifting one of its wings.

Todd and his team launch the gliders to travel between Florida and Massachusetts. The goal is to study the Gulf Stream, its effect on climate patterns and coastal sea levels along the Eastern Seaboard, and its impact on hurricanes. Todd shares this data with the Navy Oceanographic Office to help create weather-forecasting computer models. The ability to predict ocean weather is vital to the Navy’s global operations and the safety of ships at sea.

“ONR and the Navy have a long interest in gliders, since the 1990s,” said Todd. “Several of the early variants were

developed with ONR money. This area of research wouldn’t be where we’re at now without that funding.”

Another important unmanned underwater vehicle resulting from the Navy-WHOI partnership is the Remote Environmental Monitoring Units, or REMUS. This autonomous vehicle is five feet in length and resembles a torpedo. Equipped with sonar, sensors, and cameras, REMUS is ideal for mine countermeasures, seafloor mapping and surveying, and coastal monitoring.

Dr. Erin Fischell, a robotics researcher at WHOI, is trying to build on these capabilities with squadrons of four autonomous underwater vehicles (AUVs) like REMUS and Sandshark, a “micro-AUV” two feet long and weighing only 11 pounds.

Fishell hopes to create advanced communications and data-sharing networks that would allow the AUV groups to share information in real-time—expanding coverage areas and creating more detailed models of ocean currents, seafloor mapping, and geological features.

“The Navy is always trying to understand the ocean and its characteristics,” she said. “If we can create real-time models of ocean properties, they would enhance both naval acoustic and mine-countermeasure efforts to a greater degree of accuracy.”

Much of the AUV research conducted by WHOI falls under the institution’s Center for Marine Robotics, headed up by Dr. James Bellingham.

“Unmanned underwater vehicles like REMUS and gliders blend the beauty of small with the Navy’s needs,” said Bellingham. “They’re cheaper to operate and can be in a lot of places at the same time. By funding Woods Hole in this research area nearly 30 years ago, the Navy literally built the foundation of marine robotics.”

Advancing Acoustics

One of Dr. Tim Stanton’s proudest research achievements is fishy—literally. For more than a decade, the ocean physicist led efforts to develop a computer algorithm that could simulate moving schools of fish. In 2016, the Navy incorporated this technology into sonar training simulators used for both ships and aircraft.

For years, ONR sponsored Stanton’s research efforts to categorize acoustic echoes from fish based on size, species, and the density of school. This topic interests the

Navy because large, writhing masses of fish can project acoustic signals mimicking an undersea mountain or even a submarine—making it tough for sonar operators to do their jobs.

Stanton and his researchers developed a unique fish-classification system based on acoustic pitches from fish bladders. With the help of several graduate students, including a naval officer, Stanton expanded this system into the training-simulation that transitioned to the Navy's fleet.

"It's satisfying to see a scientific concept transition to an actual product used by the Navy," said Stanton. "ONR was instrumental, because it funded my research for many years. ONR truly focuses on people—finding leaders in a field, investing in them and trusting them to develop something of value. I'm a beneficiary of that generosity."

The Navy is also concerned about the changing environment in the Arctic Ocean, where melting sea ice is opening the region to expanded maritime and naval activity. Multiple ONR efforts involve launching unmanned underwater vehicles to measure temperature, salinity and ambient noise conditions beneath the ice surface—factors that can dramatically influence the effectiveness of sonar operations.

ONR sponsors one project, led by WHOI's Lee Freitag, to create an Arctic communications network—comprising specialized buoys and beacons—to allow autonomous vehicles such as gliders and REMUS units to send and receive signals underwater year-round. This is important, because thick Arctic ice prevents the vehicles from surfacing to get GPS coordinates or transmit data via satellite—even during warmer summer months.

"With this greater computing and processing power, it's possible to enhance naval capabilities in the Arctic," said Freitag. "It's a continuation of the deep expertise cultivated by decades of ONR funding."

A Legacy for the Future


In addition to funded research projects, the Navy and WHOI share an educational program that confers graduate degrees to naval officers through the Massachusetts Institute of Technology (MIT). It's called the MIT/WHOI Joint Program in Oceanography/Applied Ocean Science and Engineering.

Through a memorandum of understanding between the Navy and MIT/WHOI Joint Program, several naval officers can enroll each year for a 27-month immersion into the



oceanographic community. The program is rigorous, comprising classroom and field work, and only a handful of officers are accepted yearly.

Those officers who enter the program learn about cutting-edge technology for ocean exploration, the properties of the marine environment and how these inform naval operations. Their interactions with civilian students and scientists forge intellectual and professional bonds that could span lifetimes.

"The MIT/WHOI Joint Program is an excellent investment for both the Navy and Woods Hole," said ONR's Dr. Tom Drake. "A navy that appreciates the value of basic oceanographic research will be poised to exploit new opportunities revealed by ONR-sponsored research—and build on our valuable partnership with Woods Hole for decades to come." 

About the author:

Warren Duffie is a contractor serving as the assistant editor of *Future Force*.

AWESOME ALVIN

SHINING A LIGHT ON THE OCEAN'S DEPTHS

By Warren Duffie Jr.

AFTER 55 YEARS, THE SUBMERSIBLE ALVIN STILL HAS ITS DIVE ON.

The orange top of the submersible slides gracefully underneath the ocean's surface.

As the vehicle descends, a layer of sun-dappled water envelopes it in shades of indigo, before clouding into blackness at 650 feet. Soon, the submersible passes through the ocean's bioluminescent layer—where mysterious creatures capable of producing their own electricity flash, spark, and glow around the porthole-sized windows.

At around 6,500 feet, the temperature drops inside the submersible, making it feel like an autumn day in New England. The three passengers can see their breath fog as they put on sweaters and hats.

Excitement starts to build. The occupants—scientists and crew squeezed inside a six-foot, titanium sphere—once again review the details of the impending mission: where they'll land, whether they'll stay in one spot or travel in multiple directions, what kind of research will be performed, what types of seafloor samples will be taken.

They'll reach the ocean bottom shortly. The pilot turns on the lights and sonar, conducts a communications check with the research ship on the surface, and sheds ballast to slow down.

An hour and 45 minutes into their trip, after traveling 13,000 feet down, the explorers inside of the deep-sea submersible *Alvin* land on a rocky stretch of seafloor. As *Alvin* illuminates the alien landscape, the crooning strains of Frank Sinatra's "Fly Me to the Moon" blare over speakers.

"We like to play that song if someone is diving on *Alvin* for the first time," said senior pilot Bruce Strickrott. "It's appropriate, since the bottom of the sea really is like traveling to another planet."

A Scientific Treasure for the World

Strickrott belongs to a cadre of adventurous individuals who have taken *Alvin* to some of the deepest parts of the ocean over five decades. They enabled scientists to map undersea volcanoes and valleys; study previously unknown aquatic life; and gather a mesmerizing variety of water, rock, and biological samples that upended long-held scientific notions about the deep ocean.

Sponsored by the Office of Naval Research (ONR), and launched in 1964, *Alvin* is the world's longest-operating, deep-sea submersible. It's still going strong today, with more than 4,800 dives to its credit. The revolutionary vessel is operated by Woods Hole Oceanographic Institution (WHOI) under a charter agreement with the Navy.

"*Alvin* is a national technological treasure that enables revolutionary scientific discoveries and has helped the Navy gain a greater understanding of its primary operating environment," said Tom Drake, head of ONR's ocean battlespace and expeditionary access department. "*Alvin* opened the deep sea to humanity in ways that many considered impossible, and changed how we viewed the ocean."

Revealing the Secrets of the Deep

In the 1950s, most people knew little about the deep sea. They viewed it as a cold, dark, and flat place—devoid of any life. Submarines existed, but they didn't descend deep and they lacked windows.

In 1956, the National Academy of Sciences and National Research Council organized a symposium in Washington, DC, to figure out ways to study the deep ocean. Dr. Allyn Vine—a WHOI engineer and geophysicist and *Alvin*'s future namesake—attended the event and promoted the idea that it would be best to study the ocean floor in a deep-diving manned submersible.

Other symposium participants and attendees enthusiastically embraced this viewpoint and passed a resolution to create a national program to design vehicles that could transport humans to the "great depths of the ocean."

A major step occurred in 1960, when ONR supported Navy Lt. Don Walsh and Swiss engineer Jacques Piccard as they boarded the bathyscaphe *Trieste* and became the first humans to descend to the bottom of the ocean—the Challenger Deep—at 35,800 feet.

While the descent was an impressive feat of exploration, *Trieste* was limited in its capabilities. As a bathyscaphe, it couldn't be steered.

Trieste consisted of a small, spherical crew space slung underneath a large float resembling a balloon in both shape and function. After arriving at an area for exploration, the vessel descends to its desired depth. To return, it simply drops ballast and then simply rises to the surface.

Both the Navy and Woods Hole wanted a vessel that could be piloted, with more windows to view the surrounding seascape.

According to Victoria Kaharl's book *Water Baby*, which was published in 1989 to commemorate *Alvin*'s 25th birthday, ONR was flooded with proposals:

"ONR had received several designs for space-age underwater craft from . . . companies that hoped the navy

would be forthcoming with the construction money. Industry expectantly perceived a 'wet NASA,' an infusion of the same kind of energy, resolve and government money behind the recently created National Aeronautics and Space Administration."

In 1962, ONR hired cereal maker General Mills—which back then had a manufacturing arm dedicated to military contracts—to work with WHOI to construct *Alvin*. The contract bid was for \$498,500 (\$4,174,655 in 2019), and involved designing *Alvin* to dive to 6,000 feet.

Taking a cue from *Trieste*, which itself was modeled after balloons capable of ascending to the stratosphere, General Mills subcontracted a steel mill in Pennsylvania to make six-foot-diameter steel plates and cut them into discs that were then welded together into a strong sphere that could accommodate three people while withstanding crushing deep-sea pressure.

In an issue of *Oceanus*, WHOI's institutional magazine, Allyn Vine later wrote, "We had tried to think of almost every conceivable situation that might imperil human life, and devised ways to avoid such crises. *Alvin's* major safety feature was the crew's ability to return to the surface by releasing [a] pressure hull . . . from the sub's underbody and chassis. In that way, the crew could escape if, say, the sub's arm or other projection became entangled in debris on the bottom."

Since its 1964 unveiling, *Alvin* has provided enormous value to both the Navy and the scientific community.

In 1966, two US Air Force planes collided off the coast of Spain. One of the aircraft, carrying a hydrogen bomb, crashed and sank to the bottom of the Mediterranean Sea. *Alvin* found the bomb for the Navy two months later. In the 1980s, the Navy tasked WHOI and *Alvin* with studying the wreck sites of USS *Scorpion* (SSN 589) and USS *Thresher* (SSN 593), two nuclear submarines that sank in the 1960s.

In 1973, *Alvin* took scientists down 10,000 feet to the Mid-Atlantic Ridge, a mountainous seam stretching along the center of the Atlantic Ocean, for the first time. Instead of muddy and uniform, the ocean floor revealed itself as a diverse landscape of rocks, lava and geological features of all shapes and sizes—altering contemporary conceptions of the sea bottom.

Four years later, in 1977, *Alvin's* crew discovered deep-ocean thermal vents, nicknamed "black smokers," off the coast of South America. The presence of large colonies of clams, mussels, worms, and crabs around these scalding vents demonstrated that organisms could thrive without sunlight—the energy source for most life on land.

Other prominent *Alvin* exploits included surveying the wreck of RMS *Titanic* in 1986 and exploring deep-sea biological communities in the Gulf of Mexico to measure the effect of the Deepwater Horizon blowout and oil spill in 2010.

The discoveries of the "black smokers" and the *Titanic* wreck involved acclaimed oceanographer and former naval officer Dr. Robert Ballard.



Alvin commissioning ceremony in 1964.

ONR has invested in Ballard's research since the late 1960s, contributing to numerous ancient shipwreck discoveries as well as breakthroughs in deep-dive engineering and the study of plate tectonics

"The Office of Naval Research has played the leading role in the development of advanced deep-submergence technology, which has led to the most important discoveries to be made in the deep sea," said Ballard. "ONR also has played the leadership role in the development of autonomous vehicle systems, which are only now beginning to have a major impact on deep-sea exploration."

Alvin's accomplishments over the years have attracted many admirers—including schoolchildren, famous scientists, and influential journalists.

Even a rock star turned out to be an *Alvin* aficionado. Senior *Alvin* pilot Bruce Strickrott, who has completed more than 360 dives, recounted when a reporter toured the submersible while it was in port at WHOI.

Strickrott told the reporter how *Alvin's* crew plays a diverse selection of music during dives, with Canadian rock band Rush as a popular choice. The reporter told Strickrott he was friends with Rush guitarist Alex Lifeson. "Tell Alex that we listen to Rush on the bottom of the ocean," responded Strickrott.

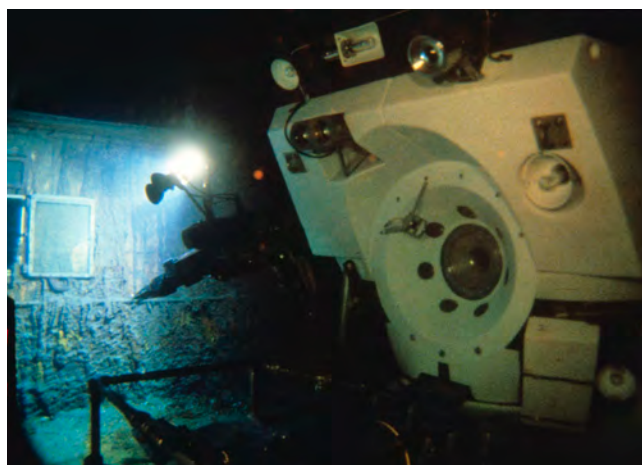
"A week or so later, I got an email from Alex, thanking us for playing Rush tunes on *Alvin*," said Strickrott. "He said he was a big fan of ours. Talk about mind-blowing."

Fifty More Years?

Today, *Alvin* is part of WHOI's National Deep Submergence Facility (NDSF), a federally funded center that operates, maintains and coordinates the use of three vital deep-ocean vehicles: *Alvin* (the lone human-occupied vehicle), the remotely operated vehicle (ROV) system *Jason/Medea*, and the autonomous underwater vehicle (AUV) *Sentry*.

The NDSF is sponsored by ONR, the National Science Foundation and the National Oceanic and Atmospheric Administration—and it oversees the deep-sea vehicles for the benefit of the entire US oceanographic community.

"You don't design a telescope for one person, you build it for all astronomers," said NDSF director Andy Bowen. "The Navy and ONR play a very important role in making these deep-exploration tools available to the scientific community."




Alvin on deck of RMS Titanic, taken from ROV Jason Jr.

One reason for *Alvin's* impressive record of success is its regular, thorough maintenance. Every three months, it undergoes maintenance and inspection. Every three to five years, WHOI puts the submersible through a six-month overhaul and modernization.

In 2014, *Alvin* completed the first of a two-part upgrade to enable it to dive down to 21,325 feet—it currently can descend to 14,764 feet. Next year, *Alvin* will undergo the second part of its planned renovation.

Besides diving deeper, other future possibilities for extending *Alvin's* exploration footprint include connecting it to smaller, sensor-packed ROVs or AUVs that would function like aquatic drones. This would allow for a larger coverage area, with *Alvin* acting as the mother ship.

"The ocean, deep or shallow, is a battlespace," said Bowen. "But it also affects the health, well-being and security of America. If we don't understand the ocean's physical and chemical dimensions, we're at a disadvantage."

Since 1964, the Navy and WHOI have contemplated the future of deep-sea research. With *Alvin* about to complete its next round of renovations to dive even deeper, this marriage of science and national security will continue to give the United States a competitive advantage underneath the ocean's surface. 

About the author:

Warren Duffie is a contractor serving as the assistant editor of *Future Force*.

UNMANNED AND UNAFRAID: THE TRANSFORMATION OF NAVAL OCEANOGRAPHY

By Dr. William Burnett and Dr. K. Todd Holland

GLIDERS AND OTHER UNMANNED UNDERSEA PLATFORMS ARE CHANGING HOW DATA IS COLLECTED AT SEA—AND ALTERING HOW MARITIME SUPERIORITY IS MAINTAINED.

The question is not will the Navy will use unmanned maritime systems in military operations, but rather how many will the Navy operate. This number will be on the low end of the scale if unmanned systems are used only for information data collection, scouting, and reconnaissance; the number will be on the high end of the scale if they are used in exclusively in combat. We already know that the Navy is using unmanned systems operationally on the low end of this scale. Now is the time to understand the lessons learned to make an enormous difference in how far and quickly the Navy can move toward the high end of the scale in the future. This article discusses the lessons learned from the naval oceanography community and how they are working closely with the Naval Research Laboratory (NRL) to incorporate new technologies and techniques into our systems.

Evolution of Unmanned Maritime Systems

For nearly two centuries, American Sailors have collected and interpreted ocean observations across the globe to conduct maritime operations and ensure military readiness.

These environmental data were received by what is now the Naval Meteorology and Oceanography Command (NMOC), which serves as the Navy's physical battlespace awareness authority. Their mission is to define and apply the physical environment from the bottom of the ocean to the stars to ensure that the Navy has the freedom of action to deter aggression, maintain freedom of the seas, and win wars. America's Navy starts with naval oceanography.

Too often, the Navy prefers to "fight through the weather" to achieve its objectives. Unfortunately, fighting through the weather basically ignores the chaotic nature of the environment that requires operators to plan ahead and respond quickly to changing conditions. Weather gets a vote in the success or failure of any mission, and improper planning or inappropriate responses to various weather or ocean conditions can result in injury or death for Sailors.

Unmanned systems take the place of operations considered dull, dirty, or dangerous. Today, thousands of remotely piloted vehicles are being operated by multiple services within the US military to: perform intelligence,

surveillance, and reconnaissance missions; suppress enemy air defenses; and conduct offensive weapon strikes. The relative ease of deploying, operating, and retrieving remotely piloted vehicles has shifted emphasis from the knowledgeable Sailor at sea to the remote shore facility, where Sailors operate unmanned vehicles in the air, on the ocean surface, and underwater from great distances. While these vehicles have rapidly multiplied, the requirement to understand the environment is still a necessity for success. The Air Force learned this lesson early on when they began operating remotely piloted aerial vehicles. They found that their vehicle loss rate increased dramatically due to issues caused by the lack of meteorological sensors to detect icing conditions in the atmosphere. In response, the Air Force initiated a program to include standard atmospheric sensors on these platforms to observe and report real-time weather conditions. Remote pilots also began to receive preflight briefings to understand the types of weather conditions they would encounter in route.

These lessons should not be lost on the Navy as it begins large-scale production and operation of unmanned systems. As more and more autonomous vehicles mature and integrate with the fleet, unmanned systems will assume key roles in defensive and offensive operations. A recent Senate report (National Defense Authorization Act for Fiscal Year 2018) states that “the Navy must increasingly leverage unmanned systems across all warfighting domains, but particularly on the sea surface and undersea.” The capability to collect oceanographic data has quickly changed with the employment of unmanned systems operating in the maritime domain. Naval oceanography is preparing to ensure the fleet can successfully navigate and conduct its operations without losing the equipment through better observation and understanding of the ocean surface and subsurface environmental conditions using unmanned vehicles.

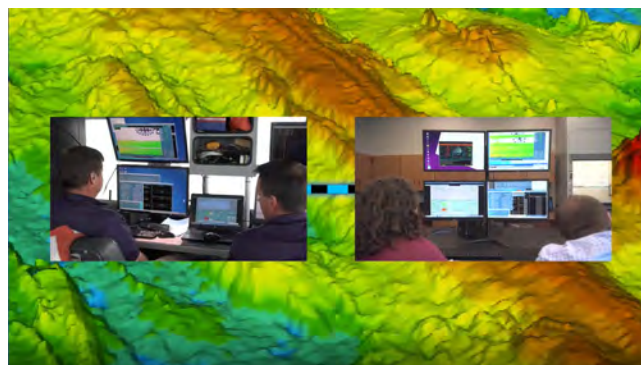
NMOC is collaborating with NRL (both of which are located at the NASA Stennis Space Center in Mississippi) to meet the unmanned maritime system challenge. This team of research scientists and fleet operators is working on new ways of employing and exploiting unmanned systems to ensure naval oceanography provides the home field advantage to all Navy away games.

Naval Oceanography and Unmanned Maritime Systems

NMOC is assigned as a task group under US Fleet Forces Command, with operational authority responsible for 1,300 military members and 1,100 civilians located at 13 subordinate commands around the world. Many of the members deploy on six oceanographic survey ships that

operate in key ocean locations, continuously surveying the ocean floor and observing oceanographic conditions to inform fleet missions. Over the past 20 years, NMOC installed a suite of autonomous underwater vehicles on the ships to conduct over 1,800 missions surveying more than 100,000 square kilometers of ocean bathymetry.

NMOC also operates a fleet of 150 buoyancy gliders that measure ocean temperature and salinity (to approximately 1,000 meters’ depth). This glider fleet has traveled almost 250,000 kilometers and already collected more oceanographic profiles than the manned oceanographic survey fleet has in 75 years of operations. The world’s only military glider operations center is located at the Naval Oceanographic Office, providing 365-days-a-year overwatch of their glider fleet as well as other types of autonomous surface vehicles. Recently, the Naval Oceanographic Office set a world’s record for deploying and piloting more than 100 underwater gliders at one time without additional manpower or vessels.



During the 2018 Advanced Naval Technology Exercise in the Mississippi Sound, operators on board an autonomous surface vessel (left side photo) watched as high-resolution, three-dimensional ocean bathymetry was collected by an autonomous underwater vehicle. The data were transmitted from the underwater vehicle to the surface vessel to a forward operating base (right side photo) where the data were quality controlled and processed in real time (background).

NMOC, with the support of NRL, is developing the tactics, techniques, and procedures to deploy, pilot, and retrieve autonomous underwater vehicles to support global operations. All oceanographic observations collected by autonomous underwater and surface vehicles must be quickly received by the Naval Oceanographic Office, given proper quality control, and then catalogued, databased, and processed for fleet use. Department of Defense shared resource center supercomputers, also located at the Naval Oceanographic Office, process these data using the Navy’s coupled ocean data assimilation system (developed by NRL) to provide realistic representations of the vertical temperature and salinity structure, especially on continental shelves. The addition of observations collected by satellites, surface ocean drifters, and profiling



Naval oceanography is able to operate a fleet of unmanned maritime systems by taking an operational life-cycle management approach. Before any system is deployed, NMOC plans their missions by taking the ocean environment into consideration. A fleet of six oceanographic survey vessels deploy the systems in theaters of operations. The Naval Oceanographic Office provides constant overwatch. Tactical control of systems can be established with in-theater assets to retrieve the equipment. Finally, a postmission analysis of the systems is conducted to determine survivability and quality control.

floats forms the data assimilation mechanism for the Navy's Global Ocean Forecast System operated by the Fleet Numerical Meteorology and Oceanography Center.

Critical information such as seawater density and sound speed are critical parameters for fleet operations to ensure proper ballasting of underwater vehicles for effective missions at required operating depths. Improper ballast could cause a depth excursion and implode the vehicle or cause the vehicle to surface unexpectedly. Fresh water outflows, internal waves, ocean currents, and mixing of different frontal boundaries must be accounted for before deployment as well as throughout operations as these abrupt changes can quickly damage and scuttle underwater vehicles.

Autonomous underwater vehicles also must know the ocean bathymetry to avoid underwater hazards. Collisions with these hazards can and do occur on platforms operated by Sailors. In January 2005, for instance, USS *San Francisco* (SSN 711) collided with an undersea mountain about 675 kilometers southeast of Guam while operating at maximum speed at a depth of 160 meters. The collision was so serious that the vessel was almost lost; accounts detail a desperate struggle for positive buoyancy to surface after the forward ballast tanks were ruptured. All efforts required an "all hands on deck" approach to save the vessel.

Autonomous underwater vehicles will not have the luxury of a full crew to salvage the platform. The cost of each vehicle can range from \$100,000 to almost \$100 million for the largest-diameter vehicle—much less than the billions for a submarine—but the loss of a number of vehicles can become quite expensive over time. The Naval Oceanographic Office is responsible for the collection and distribution of hydrographic information to the National Geospatial-Intelligence Agency to support the preparation

of maps, charts, books, and geodetic products (10 U.S. Code 7921). These bathymetry data, ocean temperatures, and salinity observations must be used in the pre-mission planning and subsequent deployment and operations of the Navy's unmanned maritime systems to ensure their missions are successful and properly retrieved.

Future Challenges

The NRL-NMOC partnership will improve autonomous vehicle mission success by bringing a holistic approach to operations. First, critical mission preplanning targeting a selected waterspace will rely on an accurate understanding of the environmental considerations for the where, when, and how to operate the platform. This understanding, provided by both advanced numerical forecasts and innovative observational approaches, will reduce the autonomous vehicle transit time and optimize the use of deployment assets such as Naval oceanography survey ships. For persistent missions (longer than a few hours), a highly automated operational overwatch, housed as the Naval Oceanographic Office's Glider Operations Center, will support 24/7 piloting and monitoring services. Once tactical control of the platform is complete, streamlined post mission operations will be implemented including novel launch and recovery assets, targeted depot-level maintenance, and high-resolution reconstruction analysis.


As the Navy's use of unmanned maritime systems moves from remotely piloted to semiautonomous to fully autonomous operations, a number of scientific and technical challenges will emerge. For example, true autonomy will require an ability not only to receive accurate predictions of the future oceanographic environment, but also to couple observations from these vehicles sensing the same environment in real time. Ideally, these observations

supporting autonomy would be directly passed back to the Naval Oceanographic Office to support future planning—as, more often than not, that observation made by the autonomous vehicle might be the only observation available in the area—but data transfer underwater and from remote areas is extremely bandwidth limited. These issues, while not yet fully defined, are now being considered and the following challenges are being addressed by the Naval Research and Development Establishment for use by naval oceanography.

- Future autonomy will require efficient processing of onboard environmental sensor data to direct decision making. Automated decision systems at NRL are being developed not only to provide guidance on the positioning of multiple surface and underwater sensors for secure and persistent battlespace characterization, but also for optimal effect of data assimilation into model forecasts. In the future, a significant portion of this decision system capability will likely be moved forward to autonomous vehicles such that the routes and selected sensors can vary throughout missions.
- Advanced communication and precision navigation technologies will need to be developed to enable autonomous swarm operations, especially across multiple domains (e.g., air, sea, and undersea). Local communication between vehicles is intimately tied to the amount of relevant information exchanged, so recent research projects to enhance onboard interpretation of information will enable greater coverage by smaller, less-expensive systems operating in a coordinated fashion and lessen the need for remote maneuver or piloting commands. Related technologies also will enable persistent operations at remote locales such as hydrographic surveying in the middle of the Pacific or operations under Arctic ice.
- Enhanced data management and analysis capabilities, most probably involving machine learning and other artificial intelligence approaches, will be needed to interpret and forecast environmental effects on autonomous systems. There are multiple efforts within the Naval Research and Development Establishment that support improved understanding and display of autonomous systems operations (including mission planning, monitoring, diagnosis, and payload management). In addition, issues concerning human factors are being researched to address the level of control between pilots and autonomous systems, including assessments of trust.

- Autonomous maritime systems require new locations to test and train new platforms, including the ability to create multiple swarms with cross-domain behaviors. Work is ongoing by NRL and the Naval Undersea Warfare Center to leverage the large physical operational area in the Mississippi Sound and the Gulf of Mexico, by using deployable/retrievable portal instrumentation systems to support multiple stand-alone exercises in operationally relevant locations.
- New approaches to enable rapid testing and evaluation of autonomous systems can overcome bureaucratic challenges with respect to validation, verification, and accreditation of new and potentially game-changing solutions. The Naval Research and Development Establishment is engaging in several exercises such as the Advanced Naval Technology Exercise and policies such as Other Transactional Authorities to engage early with fleet operators within NMOC for quick feedback so industry and academia can provide fast and flexible adjustments to meet operational requirements.

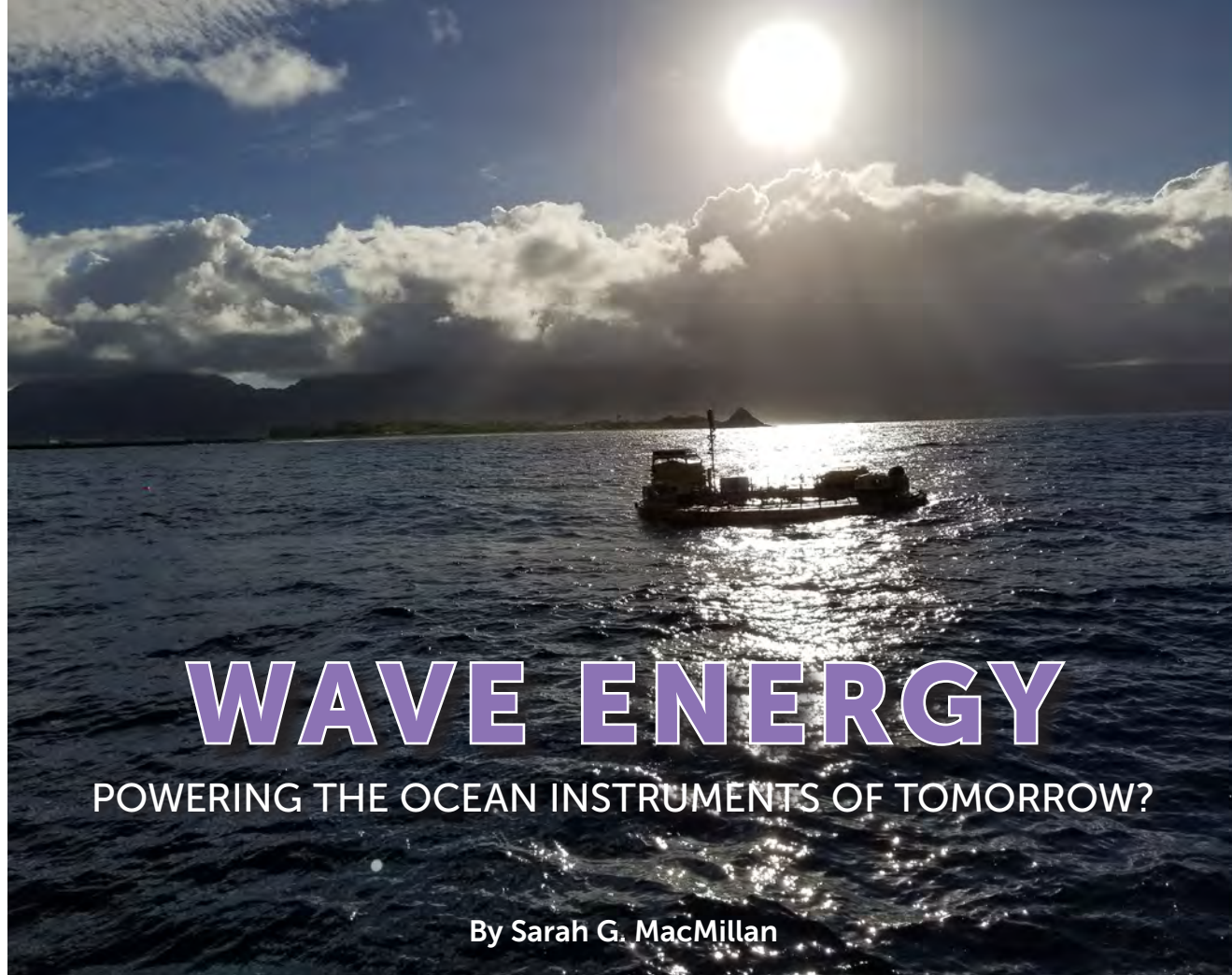
Conclusion

To answer the question poised at the beginning—we believe unmanned maritime systems will be operated in the high end of the scale. Future conflicts will be fought and won by employing fully autonomous vehicles. We hope this overview illustrates how critical our understanding of the environment is to keeping the unmanned maritime systems in the fight. Mother Nature gets a vote in every autonomous air, surface, and subsurface operation, and it is naval oceanography's responsibility to know how her vote will be cast. With the help of the Naval Research and Development Establishment, the Navy can and will maintain maritime superiority by leveraging NMOC's knowledge and capabilities with autonomous vehicles. As stated in the chief of naval operations' Design 2.0 Strategy, "The pace of competition has accelerated in many areas, achieving exponential and disruptive rates of change." The Navy must seek the advantage wherever it can be found. 

About the authors:

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WAVE ENERGY

POWERING THE OCEAN INSTRUMENTS OF TOMORROW?

By Sarah G. MacMillan

HARNESSING POWER FROM WAVES COULD PROVE TO BE A MAJOR UNTAPPED SOURCE OF ENERGY. THE WAVE ENERGY TEST SITE IN HAWAII IS ON THE FOREFRONT OF THIS IMPORTANT NEW TECHNOLOGY.

With the global rise in popularity over the past few decades of various alternative energies, from wind to solar to “green” fuels, wave energy remains far less known than other sources of power. Generating power using wave energy currently is difficult to do at the scale necessary for the electrical needs of coastal installations and communities, but a recent test by the Navy may yet help make wave energy a promising source for powering a range of ocean sensors and platforms where sufficiently sized solar panels or batteries might otherwise be impractical.

Naval Facilities Engineering Command’s (NAVFAC) Engineering and Expeditionary Warfare Center recently conducted a successful test of a Wave Energy Converter (WEC) at the Navy’s Wave Energy Test Site (WETS) off Marine Corps Base Hawaii at Kaneohe on the island of Oahu. The WEC powered a collection of oceanographic sensors continuously for 108 days, a first for wave-generated power.

In October 2018, the Applied Research Laboratory at the University of Hawaii—with funding from NAVFAC, and in partnership with the University of Washington, Fred. Olsen (a Norwegian company), and Sea Engineering (a local marine services company in Hawaii)—began testing of the Fred. Olsen “BOLT Lifesaver” WEC device. The device uses three power take-off units that convert the motion of passing waves into electrical power by way of rotary electrical generators. Control and health monitoring of these on-board systems is housed in the control center. The WEC is not connected to shore and the power generated is stored in a battery bank.


Beyond improving the device’s reliability and power performance, the primary aim of the test was to demonstrate an alternative means of powering oceanographic instrumentation without using utility-supplied electrical grid power or single-use batteries. The instrumentation, known as the Wave-powered Adaptable Monitoring Package (WAMP), was designed

and assembled by the Pacific Marine Energy Center at the University of Washington. Receiving its power from the Lifesaver, the WAMP provides persistent underwater sensing, and supports unmanned undersea vehicle (UUV) recharging using a wireless power transfer system. The WAMP is the latest in a series of demonstrations of the core AMP technology and is being used in this application to better understand the marine environment around an operational WEC buoy.

"We'd been thinking about ways to get an Adaptable Monitoring Package in the water at WETS to help with observations of rare environmental interactions—for example, do sea turtles interact with wave energy converter mooring lines?—but we were having trouble figuring out how to power it," said Dr. Brian Polagye, an associate professor of mechanical engineering at the University of Washington and WAMP project team member.

The joint Lifesaver-WAMP test was funded by NAVFAC, the Department of Energy, and the National Science Foundation. The overall effort is part of a larger joint government, academic (University of Hawaii, Hawaii Natural Energy Institute, and University of Washington), and industry research, development, test, and evaluation project. This was the world's first demonstration of the potentially transformative capability for WECs to enable persistent oceanographic observation and UUV recharging without a cable to shore.

"The common assumption has been that these technologies—like the Lifesaver—would be deployed in large arrays to provide power to coastal grids, much in the same way as terrestrial and offshore wind do today," said Polagye. "Projects like this one show that marine energy may, at least in the near-term, be better suited to providing power in the open ocean where none is available today."

Over a typical month of use, for example, if WAMP ran on battery power, it would consume the equivalent of several hundred automotive batteries. "With the Lifesaver powering us, we can collect as much data as we want for as long as we want," said Polagye. "That has the potential to transform how we think about coastal and ocean security, to say nothing of frontiers in ocean science." 

About the author:

Sarah MacMillan is a public affairs analyst with Naval Facilities Engineering Command's Engineering and Expeditionary Warfare Center.

THE WAVE ENERGY TEST SITE

WETS is a Navy-funded project that supports the research and development of renewable energy sources by providing a location off of Marine Corps Base Hawaii to test WEC devices. The WETS infrastructure includes three test berths—one each at 30-, 60-, and 80-meters depth—the last of which were installed in the fall of 2014. Each of the test berths contains three mooring legs into which a WEC device can be connected to undersea power and data communications and on-shore electrical equipment. The WAMPS test, however, purposefully did not use these on-shore connections.

The Navy and Marine Corps are able to evaluate the technical and economic feasibility of various wave energy conversion configurations, which will in turn can help pave the way for public/private sector use and benefit once these devices become more mature. Device developers can use the ocean test results to further calibrate their computer model simulations, refine their designs, and then move toward system commercialization.

Wave energy conversion device designs are of various shapes and sizes, but testing at WETS so far has focused on two specific types of devices: point absorbers and oscillating water columns. The point absorber device uses the rise and fall of the waves at a single point to convert wave energy to usable energy. An oscillating water column is a type of pneumatic wave energy converter in that it uses the rise and fall of the ocean water level inside a chamber to force the compressed air above it through a turbine or electrical generator. These devices resemble a mini-barge-life vessel floating on the water surface, whereas point absorbers look like oddly shaped marine buoys.

The WEC devices in the test area off of Marine Corps Base Hawaii do not cause any significant marine navigation restrictions because the area around the buoys are accessible and traversable to boaters and fisherman. The public, however, is prohibited from tying up to or boarding the WEC devices or associated buoys surrounding the moorings.

To date, the Navy has tested devices produced by three different companies at WETS. Results show that power from wave energy is feasible but more development is necessary to optimize the energy conversion and to reduce the overall cost of energy produced from ocean waves. Researchers have developed a keen appreciation for the difficulties of operating and maintaining WEC devices in a harsh ocean environment. Working with the Department of Energy and the University of Hawaii, the Navy currently plans on testing five additional devices within the next three years.

AN ORCHESTRA OF INSTRUMENTS

DISCOVERING THE SEA AT SCRIPPS

By Colin E. Babb

THE SCRIPPS INSTITUTION OF OCEANOGRAPHY HAS BEEN AT THE VANGUARD OF OCEAN SCIENCE FOR MORE THAN A CENTURY. ITS PARTNERSHIP WITH THE NAVY HELPED TO PUT IT THERE.

You can't escape the ocean. That's the impression a visitor gets when arriving at Scripps Institution of Oceanography (SIO), which is perched on a sloping bluff above the Pacific in La Jolla, California. You can see the water from nearly every building on the more than century-old research establishment, a place so important that an entire university campus was built to service it. (An exaggeration, perhaps, but it is undeniable that Scripps came first, and the adjoining University of California San Diego came second.) Professors and students alike find ways to fit surfing into their daily schedules. Sometime after the institution was founded, it was discovered that just off the coast was a submarine canyon, a convenient location for testing the long succession of sensors, instruments, and vehicles developed by Scripps. It is, in other words, a perfect location from which to study the sea.

Scripps existed for four decades on the edge of the California coast—both literally and figuratively—through its share of hard times and the Depression, before coming into its own during and after World War II. The partnership it formed with the Navy to help fight that war has endured in the years since because of SIO's special relationship with the Office of Naval Research (ONR). Their story, together, is very much the story of ocean science.

"Scripps has been at the center, along with Woods Hole, at building our understanding—both theoretical and

experimental, and then more recently computational—of how the ocean works in just about every realm," said Dr. Tom Drake, director of ONR's ocean battlespace and expeditionary access department.

A Home by the Sea

Established in 1903 originally as the Marine Biological Association of San Diego (in the boathouse of the Hotel del Coronado) with funds from a variety of donors, the most notable of whom was newspaper magnet E.W. Scripps, the institution moved to its present location in 1907 and became a part of the University of California in 1912. The brainchild of Berkeley professor William Ritter and San Diego doctor Fred Baker, Scripps was the first American institution dedicated to exploring and understanding the Pacific Ocean. Its purview, however, would soon encompass all the world's oceans.

In the 1930s, Scripps developed the nation's first comprehensive curriculum in oceanography, culminating in the creation of the textbook *The Oceans*, by Scripps professors Harald Sverdrup, Martin Johnston, and Richard Fleming in 1942, which would be the fundamental work on the subject in English for more than a generation. As a focal point for such expertise, Scripps inevitably became an important center for (mostly physics and acoustics) research during World War II, hosting the University of

California Division of War Research (UCDWR), which partnered closely with the Navy's nearby Radio and Sound Laboratory (a distant predecessor of today's Naval Information Warfare Center Pacific).

The postwar relationship between Scripps and the Navy was cemented on 1 July 1946, with the signing of the first contract between the oceanographic institution and the Office of Research and Inventions—only a month away from being renamed the Office of Naval Research. The contract, for \$120,000, was typical of the first few decades of ONR's relationship with Scripps and other oceanographic institutions after the war—a block grant, broadly worded, that allowed civilian scientists wide latitude on how to spend the money:

Conduct surveys and research, analyse [sic] and compile data and technical information, prepare material for charts, manuals, and reports, and foster the training of military and civilian personnel in the following fields of oceanography: permanent currents; interaction of the sea and atmosphere (including wind waves, swell and surf); the distribution of physical properties; the distribution of chemical properties; the distribution of organisms; the characteristics of the sea bottom and beaches; tides, tidal currents and destructive sea waves; the physics and distribution of sea and terrigenous [near-shore] ice. Such a program shall include both geographical investigations (surveys), experiments in the laboratory and at sea, pertinent theoretical studies and necessary travel.

Just a couple of months before, the Navy's Bureau of Ships (the predecessor of today's Naval Sea Systems Command) helped establish Scripps' new Marine Physical Laboratory (MPL), which was intended to continue, in peacetime, the Navy-relevant work Scripps had participated in with the UCDWR. According to MPL's own history of its early years, the support for the laboratory was equally if not even more open-ended than what was described in Scripps' first contract with ONR. Roger Revelle, a SIO researcher and Navy reservist who was a program manager at ONR for several years before returning to Scripps in 1948, wrote a letter for the chief of the Bureau of Ships to send to the president of the University of California, saying that if the university established the new laboratory, "the Bureau of Ships would give it tenure—which meant that we would support it indefinitely, without limit of time, as long as the Navy existed as a Navy and was concerned with submarines." After some months convincing both parties involved with the letter of its efficacy, MPL was finally founded with the Navy's support.

This multipronged support from the Navy for Scripps in the aftermath of World War II created a permanent conduit for the exchange of ideas, personnel, expertise, funding, and science that led to what many have called the "golden age of oceanography." Beginning with the Navy's loan of the tug R/V *Horizon* in 1948, most of Scripps' fleet of vessels has been either ex-naval or purpose-built ships from the Navy. Major at-sea experiments such as the Mid-Pacific Expedition in 1950 and the Capricorn Expedition, which explored various atolls in the Pacific, in 1952-53 set the standard for the kind of big, multimonth, data-gathering scientific endeavors of the time. From work on internal waves, ocean circulation and mixing, and oceanic geology to acoustics and the propagation of sound underwater, ONR's support for Scripps for more than a generation concentrated on understanding the major ocean processes. More recently, the Navy's support has shifted toward the development of more sophisticated instrumentation and data collection.

Until his passing in February 2019 at the age of 101, Scripps researcher Walter Munk was nearly the personal embodiment of the symbiotic relationship between Scripps and ONR. Joining Scripps in 1939 and studying under Harald Sverdrup, Munk became world famous for his achievements in the understanding of ocean waves, the use of sound to study ocean temperature, and a host of other fields; he also had the distinction of being the longest continuously supported ONR performer.

Partners in the Sea

Over the past 60 years, the community of federal science supporting agencies has grown considerably. Consequently, ONR accounts for less of Scripps' budget than it once did, but the Navy remains the largest single federal source of funding for SIO's research. As of 2017 (the most recent year for which figures are available), the Navy's contribution to Scripps' portfolio was about \$45 million, out of a total yearly budget of sponsored research of about \$138 million. What those dollars buy is vitally important to what Scripps does. The division of federal research labor in the 21st century is such that, while most large-scale, data-collecting research projects and expeditions often are supported by organizations such as the National Science Foundation and the National Oceanographic and Atmospheric Administration, the instruments, sensors, and vehicles used on these expeditions—i.e., the scientific infrastructure used to collect data—exist in large part through the efforts of ONR.

ONR's reliance on Scripps as a partner is equally as vital. According to Tom Drake, whose department at ONR is the Navy's main conduit for support of basic research in the ocean sciences, Scripps and the University of California San Diego are the number-two recipient of his department's basic research dollars over the past decade, right behind the Naval Research Laboratory.

"Especially now, as we are reinvigorating our look at ocean sciences under Task Force Ocean, the [chief of naval operations] rightly said the oceans, especially the undersea, are the most important thing that the United States still dominates, and we need to keep it that way," said Drake. "Scripps is a central component of Task Force Ocean. They will in fact have the single largest Task Force Ocean investment, at least at this first stage; Woods Hole will also have substantial investment. So the ability for the Navy to come to Scripps and to talk at the highest levels has always been important for the Navy's progress in ocean science."

Established in 2017 in response to a perceived need to reinvigorate the study and practice of the ocean sciences in the United States, Task Force Ocean (TFO) is working to improve partnerships between the Navy (led by the oceanographer of the Navy and ONR), academia, and the private sector. Part of TFO is of course about the monetary support of ocean science. In July 2019, ONR announced its intent to award funding for 38 research projects (including six with Scripps) proposed in response to the latest Task Force Ocean Special Notice. This funding will support 18 academic institutions, four university-affiliated research centers and federally funded research and development centers, four Navy laboratories, and three private businesses, and it will include support for 34 graduate students and 19 postdocs. These projects were selected from the more than 250 proposals received.

Another part of TFO is about helping the current generation of ocean scientists and engineers to know the Navy a little better; even at Scripps, the intimate connections between scientists and the Navy are not what they once were in the heyday of the 1950s and 1960s in the midst of the Cold War.

"I think that's the fundamental goal of TFO: it's not to force [scientists to do] the classified research, but it's to force the relevant research to the Navy," said Bill Kuperman, the director of MPL. "The problem with doing

that is that the scientists in the community, particularly the new generation of scientists, don't know what the Navy's problems are. So one of the things TFO is doing I believe is inviting academics to go on Navy cruises and stuff like that, to see what's going on."

Monitoring the Sea

The most visible and tangible product of the longstanding relationship between Scripps and the Navy is the array of sensors and unmanned vehicles both produced and used at the institution—and funded largely through the basic research efforts of ONR—that do the real grunt work of modern oceanography.

"I think this lab simply would not exist without ONR support," said Dan Rudnick, professor of climate, atmospheric science and physical oceanography. "We would not be here at all. If there's a message from me about the importance of ONR to the ocean sciences, it is that ONR has probably been the most important supporter of ocean instrumentation, and continues to be."

Among the examples of transformational instrumentation is the profiling float, a free-drifting instrument that repeatedly measures profiles of temperature and salinity from the sea surface to the deep ocean. Profiling floats were developed at Scripps and Woods Hole in the early 1990s, with support from ONR. Several generations of Scripps profiling floats (beginning with ALACE and later SOLO) have led to today's SOLO-II, which is now one of the most common types of floats used for the global Argo network. Other notable instrument developments include sea gliders, such as the Spray Glider (the model most associated with Scripps).

In the past few decades, there has been a strong shift from the development of the vehicles and instruments themselves toward new and innovative ways of using them as well as integrating them together into networks. One of these is a project Rudnick is working on called CALYPSO (Coherent Lagrangian Pathways from the Surface Ocean to Interior), a collaborative project led by Woods Hole and involving scientists from more than a dozen other institutions. During their most recent experiment in the spring off the coast of Spain, their experiments included using six gliders to look at the unique "front" where the waters of the Atlantic meet those of the Mediterranean.

Instead of a normal mission, which is to do continual profiles where the gliders descend and then come to

the surface regularly, the gliders were sent to a specific region and remained there, said Rudnick. The gliders flew down to a specific depth autonomously, found where they needed to be, and then surveyed the layer based on measurements of temperature and salinity. Instead of profiles of hours, they programmed them to stay down for one to three days at a time, increasing the amount of data recovered but also placing a premium on the gliders' navigation systems. One idea that Rudnick would like to try (but which hasn't been funded yet), is linking gliders and floats to each other in a chain where some are coming to the surface and others are staying below for long periods, all of them linked by acoustic communications.

"The proposal we put in is essentially the notion that we could put together a network of devices all tracking each other," said Rudnick. "Scientifically it would be of great value because then we'd have new ways of measuring the flow."

This progressive transformation toward sophisticated networking of vehicles and platforms is nowhere more evident than in the development of Argo, the first worldwide, persistent oceanographic monitoring system. Though the term Argo is sometimes used to refer to the individual platforms, Argo really is the entire system of floats operating around the world, constantly sending data on the oceans' salinity, temperature, and density. There are currently (August 2019) more than 3,600 floats in the system located in nearly every part of the world ocean.

Argo began as an outgrowth from the World Ocean Circulation Experiment (WOCE), a component of the World Climate Research Program, in the 1990s. A milestone in the history of the understanding of climate change, the experiment used the earliest versions of satellite-connected profile floats on a global scale for the first time.

"I think WOCE clearly demonstrated the practical nature of getting global-scale profile data from floats," said Dean Roemmich, one of the founding scientists of Argo, "it must have occurred to many of us—not just a few of us—that this was a great instrument that could be the basis of a truly global ocean observing system."

In the late 1990s, Roemmich gathered international collaborators for a permanent global ocean monitoring system, and the initial support for the idea came from ONR and the National Oceanographic Partnership Program.

Maintaining these networks, whether large ones such as Argo or small ones such as more traditional single-season

experiments, takes constant vigilance and resources. To sustain Argo's global coverage, for example, necessitates the replacement of about 700 floats a year by an international consortium of more than 25 national Argo programs, similar to the deployment levels needed to grow the system originally. Within the United States, this includes five institutional partners working together to sustain the US Argo contribution. Modern Argo floats last longer than five years, typically making hundreds of dives to 2000-meter depth and back to the sea surface every 10 days, until battery capacity is exhausted.



Scripps scientist Robert S. Dietz, left, who was a pioneer in helping to develop the theory of seafloor spreading, with Rear Adm. Rawson Bennett, chief of naval research, in 1961. (Photo by US Navy Electronics Laboratory)

Gliders, which spend more time near the surface, sometimes have "interesting" encounters. "Every once and a while we have one or two picked up, unfortunately," said Rudnick. "One person just kept it, and of course we know where it's going" because of its internal GPS unit. "It was off Point Conception—it was a commercial fisherman. He picked it up, and we always wonder why, so we asked 'why did you pick it up?'" All gliders and floats are marked with instructions and a phone number to call should something like this happen. "He didn't even call the number for a day. He finally called, and his response to 'why did you pick it up' was he thought it was military, so he figured he'd pick it up. So you thought this was a

bomb—why would it be military, and *then* you pick it up?”

Eric Terrill, director of the coastal observing research and development center, develops new sensors, vehicles, and modeling systems that have participated in a range of projects around the Pacific, from Palau east of the Philippines to Papua New Guinea to the Aleutian Islands. He and his teams have found sunken World War II aircraft in New Guinea, such as the B-25 bomber “Heaven Can Wait” discovered in October 2017 through Project Recover, a collaborative effort with the University of Delaware that looks for the underwater remains of missing U.S. service personnel. Another effort of the same project in 2018 resulted in the discovery of the wreck of the lost destroyer USS *Abner Read* (DD 526), near the Aleutian Island of Kiska.

Although the development of new vehicles and sensors often gets the most attention, researchers at Scripps also spend time trying to find new ways to stick sensors on older modes of transportation. In the never-ending quest to gather data by any means, nearly anything that spends time in the water will do. Phil Bresnahan, director of the new Scripps MakerSpace and research engineer for the Smartfin project (a collaboration with Scripps, the Surfrider Foundation, and the nonprofit Lost Bird Project), is exploring ways to stick temperature and motion sensors on surfboards.

“If there are people going out there anyway, might as well strap a sensor to them—in one way or another,” said Bresnahan.

The idea of putting sensors on surfboards makes a great deal of sense, when you realize coastal monitoring is especially expensive: you need lots of sensors, you need them well situated, and the deployment strategy can be challenging because of the dynamics of the surf zone.

“So if we have great sensors on the Scripps pier and then great sensors on Newport [Beach] pier, there’s 100 miles in between of not-really-well-observed coastal ocean,” said Bresnahan. “And this is in a very studied area.”

The sensors fit into a standard fin that can be screwed into both long and short boards; they can fit into about 60 percent of the boards currently available. The sensors automatically download their data through common cell networks the moment the boards return to the beach. The data is useful for a wide range of applications, from studying coral reefs to looking at how fish and marine

mammals move. Bresnahan hopes to get Smartfins into the hands of as many people as possible.

“Even if it’s one out of 50 people, I think that would be a huge success,” he said. “On a good day out here, there are 500 people out at the same time. If we could have 10 Smartfins in the water throughout the day at a place like this—and then in more remote locations if we could even have one out in a day—that would be fantastic.”

Traversing the Sea

Although Scripps’ academic buildings are in La Jolla, the institution’s seagoing ships—and the infrastructure that gives Scripps a global reach—are located closer to downtown San Diego at the Nimitz Marine Facility at Point Loma. Scripps has never had a manned submersible program, so all of its fleet consists of ocean-going vessels. These include the global-class R/V *Roger Revelle* and ocean-class R/V *Sally Ride*, the general purpose and coastal vessels R/V *Robert Gordon Sproul* and R/V *Bob and Betty Beyster*, as well as FLIP, the Floating Instrument Platform (see below). For most of the year, however, it is rare to see all or even most of these vessels tied up at the pier. That absence is entirely by design.

“I was here for seven years before I saw *Roger Revelle* in San Diego,” said Bruce Appelgate, who is the director of ship operations and has been at Scripps since 2007. “We operated seven and a half years away from our homeport.”

The goal with all the vessels is to maximize the amount of time that each one is out at sea doing meaningful science and collecting data. This means that much of the maintenance and logistics involved in taking care of the ships and moving personnel on and off them goes on in ports all around the world. Getting time on one of these ships does not come cheaply to the institutions that use them. *Roger Revelle*, for instance, costs about \$35,000 a day—which is just for the ship itself, and doesn’t include whatever science is being done on board.

Making it all work involves a highly coordinated, highly efficient system that spreads those costs among many organizations that are a part of UNOLS (University-National Oceanographic Laboratory System) and the various science funding agencies. Also central to this system’s success is a kind of elaborate maritime ballet that brings people and equipment out to remote locations, allowing ships to stay at sea for enormously long periods.



Scripps scientist Dean Roemmich, one of the founders of the Argo project, stands beside the latest iteration—the red plastic sphere at center—known as “Deep Argo.” (Photo by Colin E. Babb)

Appelgate used an example of a typical voyage to illustrate all this. “You leave port with one group of scientists, you get off in Honolulu, but there’s another group of scientists standing on the pier,” he said. “Then, as quick as you can you get the first group off—maybe they’ve got a day, then you’ve got two or three days to completely remobilize the vessel—maybe geologists got off and chemists are getting on. [Crewmembers then] strip the ship down after one day—it’s just a flatbed truck—and then they build it back up with whatever they’re doing with their mass spectrometers and clean rooms. And then off you go, and maybe you’re going to Pago Pago, and then they get off and there’s another group of scientists tapping their foot ready to get on.”

All of this results in a tempo of operations that is actually far busier than that of naval vessels. “We try to minimize the amount of time we spend in port, maximize the time we’re at sea doing science, and for a big ship like [Roger Revelle or Sally Ride] for us we want to have 300 operational days a year,” said Appelgate. “Compare that with a gray ship—what’s the tempo for a warship? Half of that?”

The comparison to the military is more apt than might be apparent (beyond the fact that the largest of Scripps’ vessels are owned by the Office of Naval Research on behalf of the Navy). Much as the expertise to build and maintain modern naval systems, ships, and aircraft is so highly specialized that budgets and orders for them must be essentially continuous—or the knowledge that makes them possible will literally go elsewhere—the human capital that goes into maintaining the nation’s maritime science infrastructure is just as fragile. Although there is a pipeline for new ocean scientists to enter the field each year, there are always opportunities elsewhere

to draw them out of academia. The community of engineers and support personnel who maintain the ships, equipment, and shore facilities is in some ways even more vulnerable, since they are not nearly as numerous and the lucrativeness of the commercial sector can be enticing. What they do, however, is vital.

“Every single one of our systems, whether it’s a multibeam sonar, an [acoustic Doppler current profiler], the remote stuff that we operate, or acoustic navigation systems, everything has to be maintained and calibrated,” said Appelgate. “If it’s not calibrated, the data are meaningless. Our mantra here is we want to be honest brokers of unassailable data. This is one of our biggest challenges—because each one of these things is almost a full-time job for somebody just to make sure they’re calibrated, up to spec, and operating okay. So we’ve got marine technicians that devote their careers to making sure those things work. That’s one of the interesting things about this kind of a marine operation, is that the science focus requires us to do things on ships that no other sector of the industry would ever have to worry about.”

Appelgate would love to be a part of the next generation of research vessels, which he hopes will be powered by renewable energy. This is of real concern in California, where up to 50 percent of the particulate matter in the atmosphere over the Los Angeles basin, for instance, is caused by marine shipping—not automobiles. “A couple of years ago, I worked with some friends at Sandia National Labs, who were working on the idea of zero-emission vessels,” he said. They pitched an idea to the Department of Transportation to support a feasibility study on building a zero-fossil fuel coastal vessel powered entirely by liquid hydrogen. The way it would work is that wind or solar farms on land would break down water into hydrogen and oxygen through hydrolysis, the hydrogen would be liquefied, and then it would be transported to the ship using liquid hydrogen-power trucks—making the entire pipeline carbon-neutral.

“Smaller than *Sally Ride* but bigger than *Sproul*, it’s designed as a trimaran hull vessel,” Appelgate said, “making it especially stable and providing large amounts of space in the hull for laboratories and equipment. The lack of any kind of combustion engines for propulsion or generators means it’s especially quiet.” Beyond the environmental issues, this would be particularly beneficial for research involving anything having to do with acoustics and a range of other areas as well.

Innovations with designs such as these will help keep ships relevant and central to ocean research well into the future, which Appelgate sees as a continuing partnership between manned and unmanned platforms. "In addition to all these widgets and instruments, this is one of the most important instruments," he said, pointing to a depiction of the *Roger Revelle* on his laptop screen, "that ONR supports and has historically supported. This isn't just a ship; this is a giant traveling orchestra of instruments. You never know what you're going to need. You might develop a sonar or a robot or something for a very specific need, but maintaining a broad capability across basic observing systems is something that we need to have all the time because you never know what's going to happen."

Understanding the Sea

What the ships, vehicles, and sensors at Scripps' disposal allow it to do is the kind of science that places it at the nexus of academic, government, military, and societal concerns. That intersectionality means that the persistent, networked monitoring at the center of today's ocean science simultaneously is relevant to a Navy looking for ways to create maritime systems to detect surface ships and submarines, as well as to a scientific community exploring the effects of global climate change.

Associate professor Jennifer MacKinnon, a member of the Multiscale Ocean Dynamics group at Scripps, exemplifies this convergence with her work on the Arctic. One of the projects she works on is SODA (Stratified Ocean Dynamics

of the Arctic), which is looking at physical processes in the waters at the top of the world.

"The Arctic is a bit of a funny ocean," MacKinnon said. It is unusual because the surface water is cool but fresh and relatively unsalty (a result of ice melt and river runoff). The bottom is cold and salty like a normal ocean, but there are layers in the middle that are saltier than the surface but warmer. This produces a peculiar situation where temperature can go up as you go deeper. Because of the Arctic Ocean's geography, the warmer and saltier water comes in through a limited number of points, such as the Bering Strait.

"There's a couple of reasons why we care about it," she said. "One is a climate change reason, that it's this reservoir of lurking heat. It's been there for a while, but as the ice melts and more wind is felt on the surface, the upper ocean can become more turbulent and is increasingly mixing up that heat. So there's this lurking pool of disaster of heat there." As the ice melts, you can mix up more of that lurking heat, which can accelerate the rate of ice melt, leading to a positive feedback loop.

"People think this is one of the reasons that forecast models they run for understanding the rate of sea ice decline . . . under predict the rate at which the sea ice is actually melting—it's actually melting faster," MacKinnon said.

The other reason this dynamic is particularly interesting is that these different layers of temperature and salinity



Scripps scientist Jennifer MacKinnon, far left, and members of her Multiscale Ocean Dynamics group prepare to leave the unseasonably warm waters of Nome, Alaska, for the Arctic Ocean aboard R/V *Sikuliaq* in the summer of 2018. (Photo by San Nguyen)

have unique acoustic qualities. Sound can travel within the layers, but often have trouble traveling between them. The presence of more layers of warmer water than before complicates this, and means that the Arctic the Navy is used to working with historically is changing very quickly.

"There's something about the physics of how this water subducts or dives under the cool water that it does so in discrete little 'blobs,'" which MacKinnon admitted is not a technical term, but is nonetheless eminently evocative. "And they get spat out and they start to swirl around the whole gyre." She hopes to figure out just what is happening with this process and why it occurs, not just for the science alone, but for other practical concerns as well. "I've been told by people who work more with the operational Navy that they often conceive of this like a continuous sound channel—and maybe it used to be, but it's really not now. So the acoustics implications of how you communicate through a continuous duct versus little blobs, that has quite a different effect—it scatters, it jumps, you would not use it in the same way at all."

Professor Lynne Talley likewise has her feet in two realms, as co-chair for the US portion of GO-SHIP (Global Ocean Ship-Based Hydrographic Investigations Program), a major international effort that creates detailed ship-based measurements of the sea, and SOCCOM (Southern Ocean Carbon and Climate Observations and Modeling), a float-based program off Antarctica using biogeochemical Argo floats.

GO-SHIP is essentially the gold standard of ocean data collection, where, once a decade, vessels will take the most detailed measurements possible using a wide array of instruments while sailing along preset north-south or east-west swaths of ocean. Since its establishment in 2003, the program has completed two complete cross-sections for most of these predetermined swaths that include the Atlantic, Pacific, and Indian Oceans as well as the Arctic and Antarctica. The voyages not only provide a baseline for changes in the ocean over time, but also act as calibration for all global ocean science more broadly.

"What we do is so traditional, it's what people have done forever," said Talley. "People always say, isn't it time to reevaluate that, why are you still doing that? Why are you still going on ships and making profiles?"

What these ship-based measurements do is provide the high-quality background salinity measurements that have been the only way—so far—to measure

changes in the deep ocean, anything below 2,000 meters. GO-SHIP's collection of temperature and carbon data is also vital, since 93 percent of the heat absorbed from global warming ends up in the ocean.

Talley's other big project, SOCCOM, also concentrates on understanding the ocean's carbon budget—how it goes in, where it ends up, and where it goes back out again—by concentrating on the all-important Southern Ocean. It also is the first large program involving biogeochemical sensors, which Talley hopes will be a pilot program for a global system of enhanced Argo floats that measure things such as oxygen, carbon, nitrates, and pH.

The waters surrounding the Antarctic—largely unencumbered by land masses—act like a massive heat exchanger for the world's oceans, driving much of the circulation of the oceans between the equator and the poles. Prior to SOCCOM, whose floats now are capable of collecting winter data and transmitting it during the spring thaw, no one had measured the carbon budget for this region through the entire annual cycle. Theoretically, the absorption of carbon into the ocean should equal the release of carbon back into the atmosphere.

"We have all the winter data now," said Talley, "and we can see it out-gases way more than one would have wanted it to for the budgets that we've carefully constructed over the years." Her group is now in search of where this larger uptake of carbon is originating.

Conclusion

Joined by a mutual interest in the sea, Scripps and the Navy's destinies have been entwined for much of the past century. They have shared in many of the momentous discoveries of ocean science in that time—they have shared what historian Gary Weir called, "an ocean in common." They represent what, in a sense, all modern science has become: collaborative, cooperative, tolerant of multiple ends, and dependent on multiple means.

With new questions to be asked and so much still to explore, engaging with the sea will continue to require "an orchestra of instruments." ✈

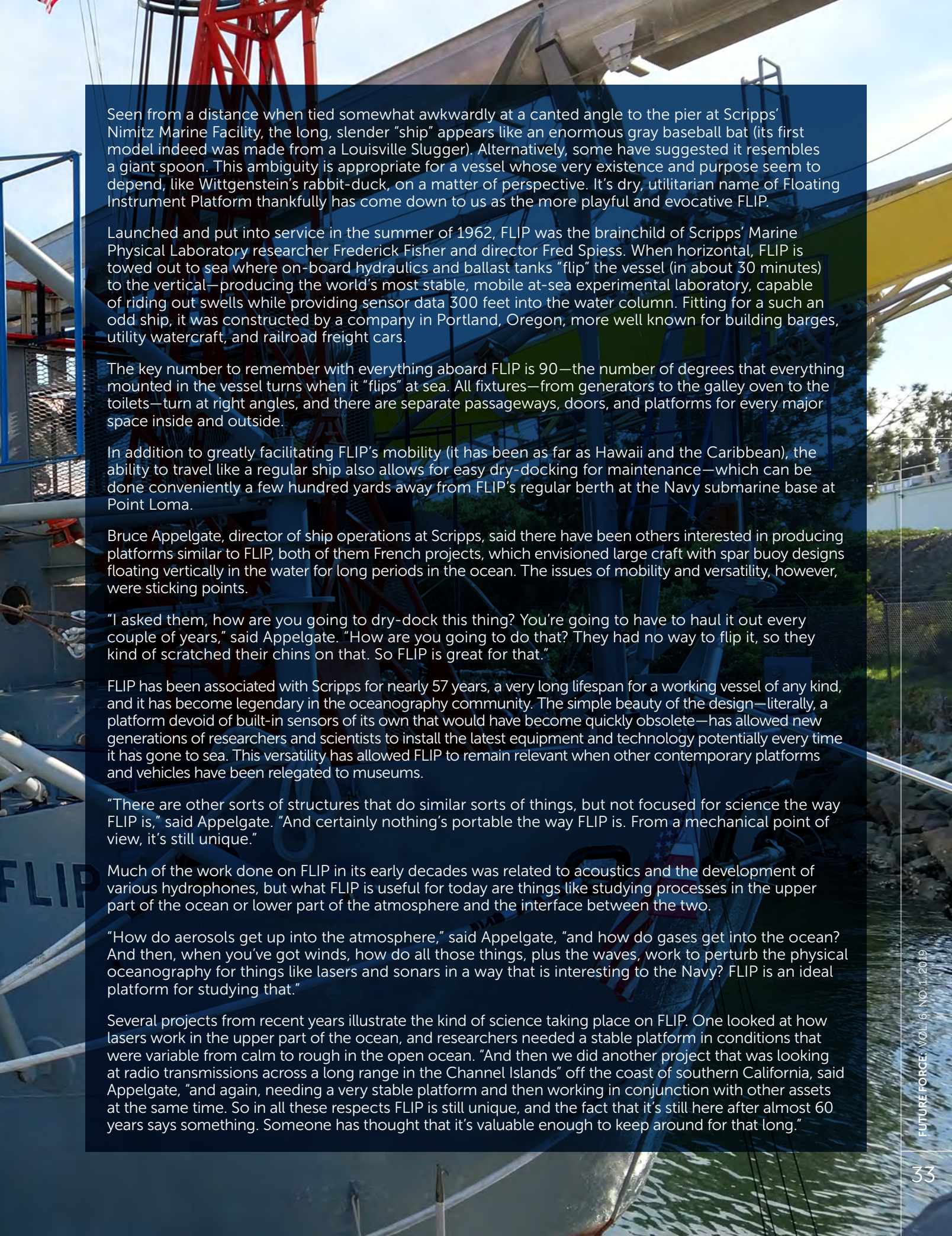
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FLIP

Still the World's Most Unusual Watercraft



Seen from a distance when tied somewhat awkwardly at a canted angle to the pier at Scripps' Nimitz Marine Facility, the long, slender "ship" appears like an enormous gray baseball bat (its first model indeed was made from a Louisville Slugger). Alternatively, some have suggested it resembles a giant spoon. This ambiguity is appropriate for a vessel whose very existence and purpose seem to depend, like Wittgenstein's rabbit-duck, on a matter of perspective. It's dry, utilitarian name of Floating Instrument Platform thankfully has come down to us as the more playful and evocative FLIP.

Launched and put into service in the summer of 1962, FLIP was the brainchild of Scripps' Marine Physical Laboratory researcher Frederick Fisher and director Fred Spiess. When horizontal, FLIP is towed out to sea where on-board hydraulics and ballast tanks "flip" the vessel (in about 30 minutes) to the vertical—producing the world's most stable, mobile at-sea experimental laboratory, capable of riding out swells while providing sensor data 300 feet into the water column. Fitting for a such an odd ship, it was constructed by a company in Portland, Oregon, more well known for building barges, utility watercraft, and railroad freight cars.

The key number to remember with everything aboard FLIP is 90—the number of degrees that everything mounted in the vessel turns when it "flips" at sea. All fixtures—from generators to the galley oven to the toilets—turn at right angles, and there are separate passageways, doors, and platforms for every major space inside and outside.

In addition to greatly facilitating FLIP's mobility (it has been as far as Hawaii and the Caribbean), the ability to travel like a regular ship also allows for easy dry-docking for maintenance—which can be done conveniently a few hundred yards away from FLIP's regular berth at the Navy submarine base at Point Loma.

Bruce Appelgate, director of ship operations at Scripps, said there have been others interested in producing platforms similar to FLIP, both of them French projects, which envisioned large craft with spar buoy designs floating vertically in the water for long periods in the ocean. The issues of mobility and versatility, however, were sticking points.

"I asked them, how are you going to dry-dock this thing? You're going to have to haul it out every couple of years," said Appelgate. "How are you going to do that? They had no way to flip it, so they kind of scratched their chins on that. So FLIP is great for that."

FLIP has been associated with Scripps for nearly 57 years, a very long lifespan for a working vessel of any kind, and it has become legendary in the oceanography community. The simple beauty of the design—literally, a platform devoid of built-in sensors of its own that would have become quickly obsolete—has allowed new generations of researchers and scientists to install the latest equipment and technology potentially every time it has gone to sea. This versatility has allowed FLIP to remain relevant when other contemporary platforms and vehicles have been relegated to museums.

"There are other sorts of structures that do similar sorts of things, but not focused for science the way FLIP is," said Appelgate. "And certainly nothing's portable the way FLIP is. From a mechanical point of view, it's still unique."

Much of the work done on FLIP in its early decades was related to acoustics and the development of various hydrophones, but what FLIP is useful for today are things like studying processes in the upper part of the ocean or lower part of the atmosphere and the interface between the two.

"How do aerosols get up into the atmosphere," said Appelgate, "and how do gases get into the ocean? And then, when you've got winds, how do all those things, plus the waves, work to perturb the physical oceanography for things like lasers and sonars in a way that is interesting to the Navy? FLIP is an ideal platform for studying that."

Several projects from recent years illustrate the kind of science taking place on FLIP. One looked at how lasers work in the upper part of the ocean, and researchers needed a stable platform in conditions that were variable from calm to rough in the open ocean. "And then we did another project that was looking at radio transmissions across a long range in the Channel Islands" off the coast of southern California, said Appelgate, "and again, needing a very stable platform and then working in conjunction with other assets at the same time. So in all these respects FLIP is still unique, and the fact that it's still here after almost 60 years says something. Someone has thought that it's valuable enough to keep around for that long."



NAVY DIVERS GET A BREAK WITH **NEW APP**

By Maison Piedfort

NAVY DIVERS HAVE ONE OF THE SERVICE'S TOUGHEST AND MOST DANGEROUS JOBS. NEW SOFTWARE IS HELPING TO MAKE THAT JOB JUST A LITTLE EASIER.

A Naval Information Warfare Center (NIWC) Atlantic team recently completed an Automated Dive Profile Data Transmission and Synchronization (Auto-DPTS) prototype aimed at streamlining the logging process for Navy dive units.

La'Keisha Williams, a NIWC Atlantic science and technology principle investigator, led the year-long management effort on the prototype, which attempts to transition Navy divers to an entirely digital platform for records keeping.

"Before Auto-DPTS, divers would have to log everything with paper and pen while still on the boat," said Williams.

"From there, divers would need to locate an internet connection in order to log into their Dive and Jump Reporting System [DJRS] account and enter data by hand."

Williams' efforts on Auto-DPTS, combined with the efforts of a contractor and the Office of Naval Research (ONR) TechSolutions, resulted in a prototype solution to provide divers with a ruggedized mobile tablet running Scuba Binary Dive Application (SBDA)-100 software.

"Metrics, such as water depth, temperature, ascent rate and other information tracked through a diver's computer, are not easily extractable," said Williams. "Now, with the adapters that we've 3D-printed, they can connect their dive computer to the tablet running the SBDA-100 software using a USB connection."

The software's algorithm for extracting and uploading the data into DJRS automates the postdive process entirely. The tablet is also Common Access Card-enabled so divers can log into their DJRS account straight from the tablet when they do an automatic upload.

"We have the software development expertise and experience to take this idea straight from the divers and put it, in physical form, right back into their hands," said Williams. "Performing effective rapid prototyping and then transitioning this technology into the hands of the fleet is a core capability of NIWC Atlantic's science and technology department."




La'Keisha Williams (left), a science and technology principal investigator at the Naval Information Warfare Center Atlantic, explains how to use the Scuba Binary Dive Application (SBDA)-100 to a Navy diver during a demonstration and evaluation underway period off the coast of Panama City, Florida. Photo by Bobby Cummings

To develop the Auto-DPTS prototype into a full working model, the Naval Experimental Diving Unit and the Naval Diving Salvage Training Center, both in Panama City Beach, Florida, are currently testing the solution in an effort to integrate the product into their divers' day-to-day training.

"We're seeing collaborative innovation and experimentation efforts across the Navy that are really changing the way we do business," said Scott Brodeur, force master diver for the Navy Expeditionary Combat Command.

Brodeur's request to ONR to automate the dive logging process initiated the project in 2017. He has aided in prototype testing since.

"We now have an application that has the ability to improve processes and give us an edge on being more ready than ever to bring combat power to wherever we're asked to operate around the globe," said Brodeur.

Testing will continue in operational environments with various dive units for the next several months. Williams and her team are currently working on certifying and accrediting the application for diver use. 

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HARD SHELL

COLLABORATION IS IMPROVING COMPOSITES FOR UNDERSEA WARFARE

By Dr. James LeBlanc

VEHICLES FOR UNDERSEA WARFARE ARE INCREASINGLY COMPLEX, DEMANDING A NEW GENERATION OF MATERIALS TO BUILD THEM. THE NAVAL UNDERSEA WARFARE CENTER IS PUTTING THESE MATERIALS THROUGH RIGOROUS TESTS.

The mission of the Naval Undersea Warfare Center (NUWC) Division Newport is to research, develop, test, evaluate, engineer, analyze, and deliver undersea warfare capabilities to expand Navy readiness. Research in ocean sciences plays a large role in the development of new technologies for the submarine fleet. Numerous research projects at NUWC include the use and exploration of composite materials in the undersea realm. In the past four years, collaborations among NUWC's technical departments and academic institutions have led to significant advances in composites research as it applies to blast/shock loading, low-temperature conditions, self-healing, nondestructive evaluation, and the effects of material aging. This high-level overview illustrates the technical projects from Navy engineers and scientists and student interns, as well as those sponsored by several other government agencies.

A key advantage to the use of fibrous composites in structural design is the ability to customize material performance to prescribed design requirements and operating environments. Fiber-reinforced polymer

(FRP) composites provide many readily recognized performance benefits, such as light weight, high strength- and stiffness-to-weight ratios, corrosion resistance, acoustic transparency, net shape manufacturing, and more. Because significant mechanical and acoustical performance advantages can be achieved beyond traditional homogeneous and isotropic materials, the Navy uses FRP composites in various surface and subsurface platforms and systems.

Composite material selections often are made based on empirical data derived from material level tests, prototype experiments, and analytical or computational mechanics models for the required operating conditions. Proper selections of the fabric architectures, fiber and matrix materials, ply stacking arrangements, etc., can yield significant mechanical and acoustical performance advantages over traditional structural materials. Selections often are based, however, on experiments and analyses performed without consideration of extreme operating temperatures and water ingress.

Response to Underwater Explosions

One research project is developing advanced experimental and computational modeling methods and practices to study the response of composite materials to a range of dynamic and shock loading conditions—namely, underwater explosions. Through the evolution of the research, experimental and modeling methods have progressed from the study of far-field detonations to more recently near-field detonation effects. The emphasis of the research is to evaluate the effects of laminate properties on the response of composite plates to underwater explosive loading. The purpose is to further the understanding of these effects on the transient response and damage evolution characteristics of composite laminates while also developing validated computational modeling approaches.

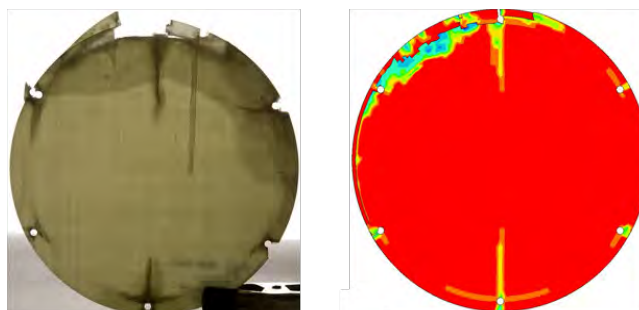
The use of computational modeling methods provides a means for the efficient study of a large range of variables to identify those parameters that most heavily influence the transient response of these structures. The identification of those material properties and laminate constructions that result in superior performance and blast resistance may form the basis for future design of naval vessels and structures when shock/blast is a concern for warfighter safety. Recently, the effects of blast mitigating laminate modifications as well as the incorporation of elastomeric coatings such as polyurea have been studied.

Low-Temperature Seawater

In 2018, a detailed experimental effort was initiated to study the effects of low temperatures associated with Arctic and deep-depth environments on the mechanical and acoustic behavior of composite materials. The objective to develop a knowledge base of the temperature effects to guide the optimizing of fiber and matrix material selections. The mechanical and acoustic properties at typical operating temperatures (around 15 to 20 degrees Celsius) have been extensively studied; there is, however, limited data pertaining to the response of these materials at the lower temperatures associated with Arctic seawater and those found at extreme depths. The goal is to support the design of Navy structures, vessels, and components operating in cold temperatures, submerged environments such as the Arctic regions, and at the deep depths of the ocean. The study consists of both mechanical characterization as well as water ingress trends using both experimental and analytical approaches. The research conducted under this program represents a significant collaboration among several of NUWC's technical departments.

Residual Strength after Exposure to Blast Loading

Through experimental techniques, another research project identifies how shock damage affects a composite structure's ability to function after shock in submerged operations. A methodology was developed to detect and evaluate damage using current technology available at NUWC and the University of Rhode Island (URI). The approach includes shock tube experiments, and nondestructive flash infrared thermography and terahertz imaging of the composite laminate panels before and after shock. The through-thickness images are used to quantify the panels' damage prior to conducting residual strength tests on each damaged panel. The quantified damage and residual strength data is used to develop a linear damage-strength prediction equation for the composite after exposure to blast loading. Data on the residual strength of composite materials might allow the Navy to improve the design of composite structures when exposure to blast loading is a concern.



Material damage during test (left), material damage from simulation (right).

Self-Healing Composites

A recently initiated project is aimed at developing and characterizing a self-healing resin system within a composite material, capable of autonomous repair of the polymer matrix. The research investigates the mechanical properties of a fiber-reinforced polymer composite that is capable of self-repairing cracks in the polymer matrix without human intervention, as well as whether or not it is a viable material alternative for structures in an undersea environment where damage is likely to occur. Composite materials are known to be highly susceptible to damaging cracks or tears deep within the structure that are difficult to detect and sometimes impossible to repair. This is especially true at sea because the risk for damage from high pressures at deep depths or contact with foreign objects is significantly increased. Even small cracks and tears from submergence and thermal cycling cause a notable decrease in the structural integrity and mechanical strength of the



Submarine sail exposed to low temperatures.

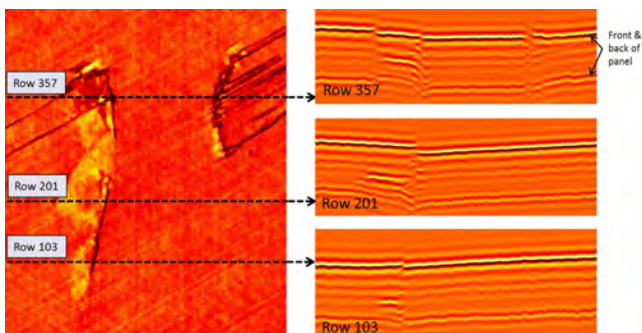
composite material. This can lead to more severe damage to the structure, negatively affecting its functionality.

This research will identify and fabricate an effective healing system that works in seawater, as well as quantify the principal mechanical properties of the self-healing material with added fibers. The effectiveness of the self-healing material samples will be determined through damage-inducing experiments and post-test evaluation techniques. The self-healing material system and evaluation techniques can be used by the Navy to develop self-healing polymers and composite materials for undersea systems—leading to longer life, less maintenance, and lower costs.

Shock Response in Marine Environments

Within the Navy there is interest in constructing new vehicles and structures from composite materials so that their high strength-to-weight ratios may be exploited, resulting in lighter structural components that allow more equipment to be packaged into an equivalent volume. When these structures are deployed in marine environments they are subjected to aggressive conditions, including high-salinity seawater and/or salt spray that can significantly degrade their structural performance over time. These effects are of particular concern when composite vehicles are deployed in a military setting where they may be subjected to shock and/or blast loading at any point in their service life.

This program investigates how composite materials that have been exposed to a marine environment for



Terahertz images of a damaged composite panel showing depth and location of cracks and delaminations.

a prolonged time respond to shock events and how that response differs from an equivalent nonexposed structure. The effort quantifies the effect of prolonged exposure to aggressive conditions on the shock response of a composite structure. This has been accomplished using the high-pressure tank at URI with underwater explosion loading experiments and accelerated life aging techniques, as well as numerical methods developed by NUWC in collaboration with air-driven shock tube experimental methods developed by URI researchers.

Future Projects

In 2019, NUWC and URI will collaborate to investigate the effects of long-term seawater immersion combined with large depth pressure effects in the structural integrity of composite structures. The research program is conducted through the ONR naval undersea research program. Specifically, the study will investigate the effects of combined extreme hydrostatic depth pressure and long-term seawater submergence on the integrity and performance of composite materials to identify the degrading effects of the environment. The emphasis will be on understanding the fundamental physical mechanisms of seawater ingress when combined with the driving force of deep ocean pressures, as well as identifying the adverse effects on the structural integrity of a vehicle when subjected to this combined loading environment.

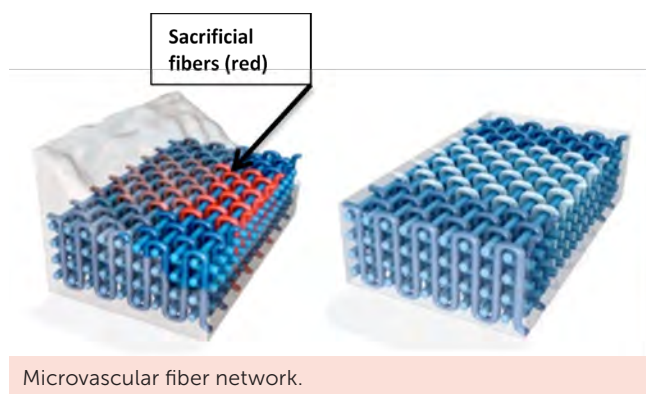
Corresponding computational models of the experiments will be implemented to support the development of validated modeling practices for the reduction of expensive qualification testing. There is a significant need to understand not only how seawater immersion degrades the mechanical properties for these materials, but also how the degradation is influenced by the coupling force of large hydrostatic pressures. The degradation caused by prolonged submersion will be simulated by employing accelerated life methods conducted under high-pressure loading.

Collaborating with Academia

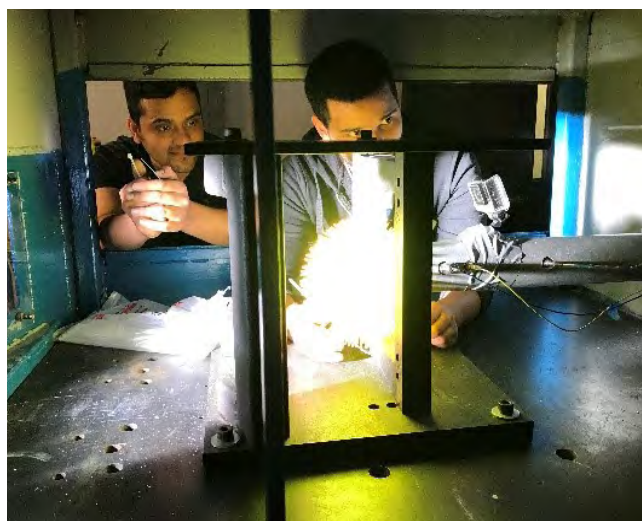
Several of the research projects represent a collaboration between NUWC and URI through the Naval Engineering Education Consortium (NEEC). Participation in the NEEC program by NUWC mentors has offered the opportunity to engage with graduate students in both an academic role as well as a NUWC internship role. While each aspect is related to the overall program objectives, the

individual components provide unique opportunities from a mentoring perspective. While students are attending university during the academic year the mentoring role is primarily focused on the technical execution of the project and providing a certain level of guidance at it relates to the naval relevance of the research. Through a program such as NEEC, Navy mentors are able to bring a certain focus to the research program to help alignment with current and future fleet needs rather than an open-ended research program.

The benefits of this are substantial in that NUWC has the opportunity to influence the path of the research through technical guidance to align with Navy objectives for future adoption of the results, while also providing graduate students with the feedback that their research has real-world relevance. During the summer portion of the NEEC program, the mentor role transitions to a professional workplace mentoring environment. Being situated in a Navy laboratory allows students to engage with working engineers and scientists on a daily basis. These interactions allow students to become directly involved and integrated with the working groups that are solving problems that, while related, might be otherwise outside students' research programs.



"The NEEC program is important to the warfare centers, because it helps attract new professionals across technical fields associated with the complex technologies used by the Navy, and increases and maintains a knowledge base for these increasingly sophisticated technologies," said Dr. Elizabeth A. Magliula, NEEC director at NUWC Division Newport. "NEEC gives students an opportunity to work at unique facilities, encourages them to think critically, refine their problem-solving skills, and seek out innovative solutions. University projects parallel warfare center technical capabilities, including advanced materials, advanced sensor technologies, autonomous systems, machine learning, neural networks, and artificial intelligence."



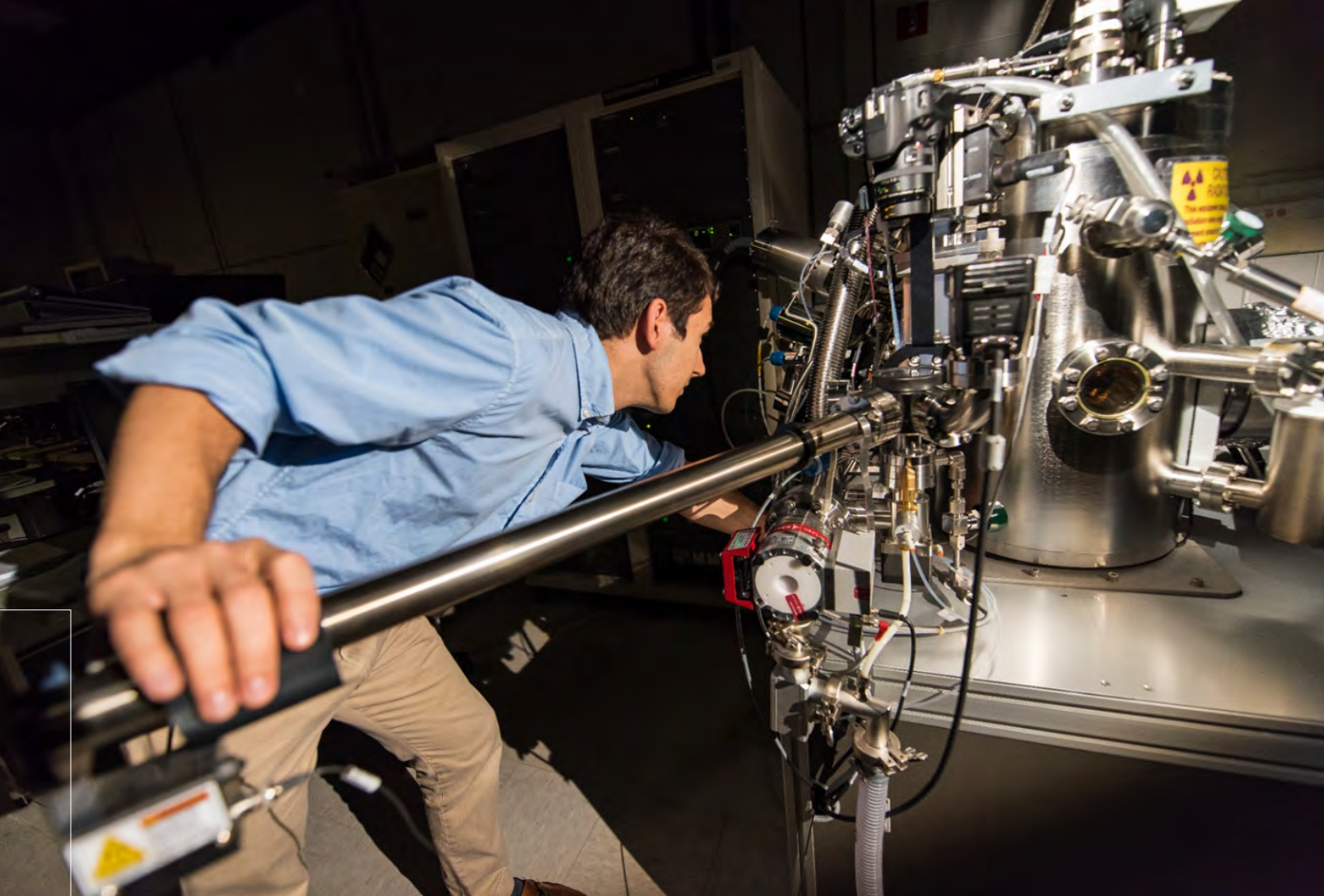
URI students prepare an air blast loading experiment.

The continually increasing demands of structural requirements and performance are driving a large number of industries and organizations, including the Navy, to seek out and leverage the benefits of advanced material systems such as composite materials. These materials are finding increased roles in applications ranging from surface ship radomes and deckhouses, submarine components, and advanced hull forms. The benefits afforded by these novel material systems include high performance-to-weight ratios, overall reductions in maintenance, the ability to manufacture complex geometries, and improved performance in aggressive environmental conditions.

With the increased use of these materials, consideration also must be given to the extreme loading conditions that are imparted to them in the expected operating theatres. A fundamental understanding is needed of the material response when exposed to conditions such as impact, shock, hydrostatic pressures, and temperature extremes. It is with these goals in mind that NUWC is engaged in composite materials research programs that aim not only to develop a fundamental understanding of these advanced materials to support increased adoption into the fleet, but also to foster the growth of the future research workforce through meaningful collaborations with academia. ✈

About the author:

Dr. LeBlanc serves as the chief scientist of the Platform and Payload Integration Department at the Naval Undersea Warfare Center Division Newport.



THERE'S A BETTER WAY TO GET BATTERIES FOR THE NAVY

By Nicholas E. M. Pasquini

AS THE QUANTITY OF BATTERY-POWERED SYSTEMS IN THE NAVY AND MARINE CORPS INCREASES, THE CONCERN FOR BATTERY QUALITY HAS RISEN. A NEW ENTERPRISE HAS BEEN GIVEN THE JOB OF ENSURING THE DEPARTMENT OF THE NAVY'S BATTERIES LAST LONGER—AND STAY SAFE.

The Naval Sea Systems Command's Marine Engineering Division and warfare centers recently established the Navy Battery Development and Safety Enterprise to support and enhance the Department of the Navy's compliance with lithium battery safety requirements, and to accelerate the fielding of advanced lithium-ion-enabled capabilities to the fleet.

"Most importantly, we need to get required energy storage to the warfighter, faster, more effectively, and in a format that is deployable," said William Bray, deputy assistant secretary of the Navy for research, development, test, and evaluation. "If we can get advanced batteries into the hands of the warfighter at a lower cost, while enhancing readiness and reducing sustainment and logistics requirement costs, then we are winning—delivering lethal capacity, while driving affordability in advanced energy storage."

The enterprise, which officially began work in October 2018 at the Washington Navy Yard, is resourced initially with \$1.5 million, with plans for the next two fiscal years of \$3.3 million and \$7.4 million, respectively.

Department of Defense applications require optimal energy management and storage for today's Sailors and Marines, who carry devices such as computers, GPS, smart phones, optical sights, night vision, radios, and thermal imagers in austere and desolate environments. There have been many lithium battery systems fielded in the Navy and that advanced capability is steadily growing, including developments for unmanned systems in every domain, directed energy weapons, and dismounted warfighter applications for the Marine Corps.

"Through coordinated [systems command] effort and an eventual [Department of the Navy] battery policy, the Navy Battery Development and Safety Enterprise will also seek to develop family of systems and scalable technologies (commonality) to support future cost reductions of lithium batteries," said Tamera Barr, battery development and safety lead.

"In recent years, systems commands and even individual program management offices in the systems commands have been acquiring lithium batteries and battery systems on a program by program need, resulting in many unique systems, from large-scale unmanned underwater vehicles to small-scale unmanned aerial vehicles being procured, and a stove piping of battery development efforts across the Navy," said Barr.

The new enterprise will coordinate battery efforts across the Navy, Marine Corps, and the Naval Research and Development Establishment to procure and deploy batteries for combat systems more efficiently, safely, and cost effectively, she said.

"Unlike anything done in decades past, it's the first time 'Big Navy' has recognized a need to stand up an enterprise specifically to improve the speed with which we certify lithium batteries, at lower cost, without compromising the growing concern of safety," said Eric Shields, advanced power and energy branch manager at Naval Surface Warfare Center (NSWC) Carderock Division. "This has, does, and will impact hundreds of millions of dollars in battery procurements over the coming decade and is a major positive breakthrough that will benefit greater than 40 . . . program offices."

The Navy Battery Development and Safety Enterprise will support programs including the Extra Large Unmanned Undersea Vehicle Orca, the Large Displacement

Unmanned Undersea Vehicle Snakehead, the Mark 18 Mod 2 mine countermeasures system, the Energy Magazine Laser, and many more.

NSWC Carderock Division and NSWC Crane Division are the technical agents for the Navy's lithium battery safety program and work closely with NSWC Philadelphia Division and Naval Undersea Warfare Center (NUWC) Division Newport for surface ship and undersea systems integration. "The four labs operate very efficiently as a unit and this collaboration has positively impacted what we've been able to accomplish in the last four years," Shields said.

As the warfare centers have placed increased emphasis on collaboration, a quarterly warfare center collaboration summit was created for various divisions to discuss power-related challenges and opportunities, as well as to tour each other's facilities and capabilities.

"This has led to many instances of collaboration and efficiency with battery testing, battery certification, Naval Innovative Science and Engineering . . . program projects, operational energy projects, and battery commonality initiatives," said Jason Leonard, energy systems specialized test and evaluation branch manager at Crane. "This collaboration also identified areas of duplication of technical capability, which resulted in a reduction of waste. Each of the warfare centers has particular areas of expertise and experience, and understanding those areas enables them to be combined efficiently to obtain a complete capability for the warfighter. An increased level of trust between warfare center leadership has been established and will continue to foster a cooperative culture where the capabilities of the joint team is larger than any of the single warfare centers by themselves."

There are several Defense Department power-related communities of practice that meet periodically to collaborate and discuss power needs and issues. These are typically attended by Navy, Army, and Marine Corps representatives. In addition, large-scale conferences are held each year enabling further collaboration between the military, academia, and industry.

"Through these various meetings, a true community of practice has been established where power and energy subject matter experts and end users grow to know each other and can collaborate with each other, sharing knowledge and lessons learned across the power and energy community," said Leonard.

Streamlining Processes

Lithium batteries offer many advantages to warfighters,

including increased energy, lower weight, and longer cycle life. "As such, many programs are looking to integrate lithium batteries into platforms that have not traditionally used them," Leonard said. "With that increased energy comes increased risk if a battery failure was to occur, especially in aircraft and undersea platforms where the operator is collocated with the battery and cannot easily escape."

The Navy lithium battery certification process evaluates lithium battery and power systems to identify worst-case failure modes and system level impacts so that mitigations can be implemented to enable safe use, storage, and transport of lithium technologies on Navy and other platforms.

"The newly established Battery Development & Safety Enterprise will centralize and streamline this process, providing appropriate resources and authority to enable this technology to be used by our warfighter in a safe manner," said Leonard. "The end result will be increased capability delivered to the warfighter at a quicker pace, while ensuring high levels of safety."

Philadelphia Division's primary focus areas are on high-power shipboard batteries and lithium battery facilities. "Shipboard batteries range from small uninterruptible power supply batteries, through large, 1000 volts DC batteries that support major weapon developments like lasers and railgun," said Dr. John Heinzl, systems integration manager for future power and energy storage architectures at Philadelphia. "Facilities are structures and related systems—sensing, venting, firefighting, etc.—that allow batteries to be safely stored and maintained aboard Navy ships. Both of these are critical, because they provide surety of power, high power capabilities that mission loads require, and allow the batteries, be they for aircraft, unmanned vehicles, or embedded in a space, to be safely accommodated."

This necessitates partnering, and building of the appropriate competencies, said Heinzl. Philadelphia Division and other divisions support Office of Naval Research and Naval Sea Systems Command developments of energy storage technology, he said, and a wide variety of programs and opportunities are leveraged to build prototypes and mature modeling and simulation capabilities.

"This includes thermal management modeling and simulation capability, development of non-propagating high power designs, and advanced sensors and controls," said Heinzl. "The Small Business Innovation Research and Small Business Technology Transfer programs are also employed heavily to develop advanced technology where gaps are observed. Additionally, NSWC Philadelphia Division executes coordinated projects with other Navy and service labs, including collaborative [Naval Innovative Science and Engineering] projects and [Office of the Secretary of Defense] efforts."

NUWC Division Newport is focused on developing and delivering undersea warfare systems. "These systems are typically embarked on submarine platforms, which makes lithium-ion battery certification



An experiment validates the applicability of water for a lithium-ion battery casualty suppression system. Unmanned underwater vehicles do not typically use see-through bulkheads and endcaps, but during this experiment polycarbonate end-caps were used on the test article to allow direct imaging of behaviors in the battery vessel during casualty initiation, fire progression, fire-suppression, and resolution of the test event at Naval Surface Warfare Center Carderock Division. Photo by NSWC Carderock Division Imaging Branch

even more challenging,” said Dr. Joseph Fontaine, mechanical engineer at Newport. “We typically serve as the lead system integrator; as lead integrator we work closely across the technical warrant holder and ship design manager community to develop technologies that are capable of achieving certification. The new alignment will help us achieve certification more efficiently by standardizing the testing that both NSWC Crane and Carderock perform in support of certification.”

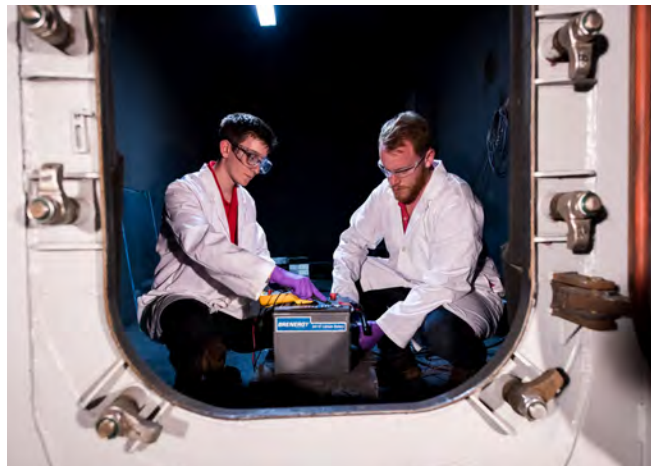
Division Newport also provides technical oversight and leadership in the execution of the unmanned systems integrated product team power and energy unmanned underwater vehicle family of systems effort. “This requires close coordination with all the warfare centers and SEA 05 community to achieve success,” said Fontaine. “Under this effort working closely with PMS 406 and 394, we developed the submarine lithium-ion battery embarkation strategy of prevention, detection, and mitigation.”

“A major goal of the stand-up of this enterprise will be to positively impact the Navy’s compliance with lithium battery safety requirements by improving the throughput of these safety reviews at [Naval Sea Systems Command] and standardize cost and schedule estimates so that program managers can plan for them,” said Julie Simmons, technical area lead for lithium battery safety at Carderock Division.

Looking to the Future

Philadelphia Division also works closely with Dahlgren Division to emphasize the holistic considerations of stored energy in electric weapons systems installed on Navy ships. According to Heinzl, there are not that many high-density, permanently embedded battery systems in use in the fleet, but as future platforms are developed and electric weapons and directed energy are rolled out these systems and capabilities will have to be considered for most every ship class.

The new enterprise will help to further coordinate and centralize certain processes that can offer efficiencies and reduce certain burdens of execution. “It is well known, for example, that the safety testing processes consume a number of battery assets, so are extremely expensive to execute and challenging for programs to navigate,” Heinzl said. “The battery enterprise will strive to reduce cumbersome practices, and ensure that the technical agents who help implement the processes



Louis Levine (left) and Jacob Helmers (right) conduct test setup of a large format lithium-ion battery for use in Marine Corps and Army tactical vehicle applications in the Carderock Division battery lab. Photo by NSWC Carderock Division Imaging Branch

and evaluations are appropriately resourced and able to broadly support Navy initiatives.”

The new Battery Development and Safety Enterprise also will help to establish a battery database, a Navy first. “While it’s not a guarantee that a specific battery can be selected from a list and placed from one application into another without test, it will help to ensure awareness and streamline the process as systems of similar scale and requirement get fielded across a variety of ship classes for a variety of reasons,” said Heinzl.

“The other key element of standing up a battery enterprise is the alignment with DASN RDT&E’s office, and especially the Operational Energy Office,” said Heinzl. “That really is important because from their level, all angles of the Navy’s energy storage world can be more readily engaged and involved. There’s no guarantee that a broad number of applications will be able to be fit with few solutions, but awareness and policy, coupled with the enterprise’s initiatives, will allow us to find efficiencies where we can, reuse test results and information where practical, and in time, strive to utilize a common set of components, systems and support equipment where it makes sense for the fleet.” ✈

About the author:

Nicholas Pasquini is a writer with US Naval Research Laboratory public affairs.



MAPPING THE OCEANS FOR SOUND

PREDICTING
SONAR-SEABED
INTERACTION



A PROJECT AT THE NAVAL RESEARCH LABORATORY IS BUILDING A MODEL OF THE BOTTOM OF THE OCEAN TO HELP PREDICT HOW SOUND IS AFFECTING BY GEOLOGY ON A GLOBAL SCALE.

The Navy can gain a competitive edge over its adversaries by marshalling its knowledge of the material properties and processes affecting the ocean floor.

At the helm of this effort is US Naval Research Laboratory (NRL) geologist Dr. Warren Wood, whose team is collaborating with the University of Sydney, the University of Colorado Boulder, and the US Geological Survey on critical research for the development of a conceptual model that predicts the ocean's sea floor features and how they change over time. It's called the Global Predictive Seabed Model (GPSM).

GPSM will provide Navy decision makers the layout of the ocean floor, enabling a richer assessment of how sonar should interact with the seafloor environment in a particular location. This insight can help determine the nature of sonar anomalies, and how to respond to them.

Understanding the physical structures of the seafloor, and when, how, and where they change is of great interest to the Navy.

The Navy uses sonar to identify submarines and various objects under the water. Different objects respond differently to inputs from the physical environment around them. The makeup of the ocean floor is a factor in how sound propagates, and therefore, how sonar reacts to it.

"We want to understand the seafloor the same way we understand the ocean and the atmosphere—with a global model," Wood said. "Many naval operations use sound propagation properties such as sound speed, density, and acoustic attenuation of sound energy to estimate sonar performance. We have to know how sound is going to interact with the environment before we can understand how it reacts to an anomaly."

GPSM is designed to look at fundamental properties of the seabed and use that information to calculate the sound interaction with the seafloor.

According to Wood, GPSM is capable of looking at the geology of the entire world, but his research today is focused on the ocean. To develop this global model, he is started with what he calls a “nowcast.”

The nowcast is a model used to tell a researcher a present condition or something happening in the very near future. Nowcasts are very common in meteorology—think checking the weather app on your smart phone. That information is fed into the predictive models, also known as forecasts, to help improve the model’s algorithms, resulting in improved future accuracy. That same concept can be applied to geology to identify what is there now, and eventually, what will be there in the future.

“We’re identifying what sediment currently exists in these areas all over the world and consolidating it into one system called a nowcast,” said Wood. “Once we have the nowcast, we will move forward with the forecast.”

Wood said the data currently used for the nowcast is collected from public sources, but the system can use data from any source. Included among the many data points it currently uses are sediment information collected on grain size, grain type, temperature, and porosity.

Field data such as sub-bottom profiles help researchers identify and characterize seafloor sediment from the sea surface. These data, acquired from a distance, are incredibly important for acoustic research, because they help constrain characteristics such as the ratio of clay to the total solid materials.

Wood also collects data through research conducted in the lab and field for use in his numerical predictions. At his lab within the Stennis Space Center in Mississippi, Wood conducts sediment physics tests that allow for careful, direct measurements of the interactions between sound and sediments.

Although Wood can learn a great deal from his own research, he also relies heavily on input from the global geophysical community to identify the location and types of sediment found throughout the world. Although operational security requires that some of the data remain classified, Wood hopes much of the research can be conducted in the public domain to facilitate knowledge sharing and collaboration.

“This is a new way of thinking about the seafloor, and it requires a community to support it,” said Wood. “We

have to think about how to collect and ingest data from Navy survey vessels, as well as commercial and academic groups. We need everyone on the same page to determine how acoustic measurements could be incorporated into the global model to make it more accurate.”

In addition to examining geophysical structures, GPSM will predict the likelihood of encountering a certain fraction of microorganisms. Wood and other researchers are developing a sediment system that will tell researchers what sediment is terrigenous (material from the land) or biogenous (material from plants and animals).

“There are many aspects of the seafloor of interest to the geophysical community as well as to the Navy and we want to build as comprehensive of a model as possible, which includes gravity and magnetics, bathymetry, total organic carbon, etc.,” said Wood.

Geomorphic Processes That Shape the World’s Oceans

Out of sight and often out of mind, vibrant geomorphic processes reshape our world’s oceans at any given moment. To help divide, understand, and study the ocean floor, it is generally thought of as three different environments: the shelf, slope, and deep ocean. Each area of the ocean floor boasts unique geological features that influence how sound propagates.

“We are looking into acoustic interaction with the seafloor,” said Wood. “Because of the change in temperature of water column with depth, the sound actually travels mostly horizontally, bending up and down in what is called a sound channel. Sometimes the sound interacts with the sea surface, and sometimes it interacts with the seafloor as it refracts through a sound channel. Greater interaction with the sea surface or seafloor generally results in greater loss of sound energy—important for knowing how far the sound will travel, and how far away certain sounds can be detected.”

Wood operates under the hypothesis that if his team can predict the geology, they will be able to predict the sound interaction, and therefore the distance the sound will travel. That area Warren seeks to identify and forecast begins at a place many surfers, boaters, and other water enthusiasts are familiar with: sea level.

The continental shelf ranges from sea level to about 200 meters deep and includes beaches, estuaries, and other coastal areas. Earth contains nearly 372,000 miles of

coastline with varying sediment. Sediment is the loose sand, clay, silt, and other soil particles that settle at the bottom of a body of water. It can be created through soil erosion or from the decomposition of plants and animals, and can range in size from microscopic clay particles to large boulders. Ocean currents and rivers can carry sediment extended distances, so as ocean currents and sea levels change, there is an increased likelihood for change in sediment deposits.

The area that extends from the shelf about 200 to 4,000 meters deep is known as the continental slope. While the shelf tends to be sandy, the slope tends to be rich in fine-grained sediment, including clay. The total rate of sedimentation slows on the slope, so by fraction it contains more contributions from dead microorganisms, often made of calcium carbonate or silicon. When they die, their remnants accumulate and contribute to the overall sediment load.

The slope transitions into the deep ocean at about 4,000 meters, and most of the ocean is between 4,000 to 6,000 meters deep, according to Wood. Although it may be far from land, the deep seafloor can contain terrestrial wind-blown clay, and sediments dropped from melting ice bergs, as well as dead microorganisms, all of which interact differently with sound.

Deep in the ocean and far from human view live a variety of microbial communities prospering in what for us would be a very unforgiving environment. These communities feast on a variety of things, including buried organic matter, methane seeping from the sediments below, or even large marine life, such as dead whales. Just like on the slope, these living and deceased organisms, particularly the shells and skeletons they leave behind, impact the environment and therefore the way sound interacts with the deep ocean environment.

Even events hundreds, or even thousands of kilometers away can change the composition of the sea bed. Volcanic eruptions create ash that is carried by wind and then dropped throughout the ocean. When the ash sinks, it creates layers on the seafloor that mix with microorganisms and clay. It's common for clay to also be carried from afar. Clay from the Gobi Desert is often carried by wind thousands of kilometers until it is deposited into the Pacific Ocean.

These natural processes are not tracked in real time on a global scale. GPSM seeks to be the first model to both

understand current conditions and eventually predict changes for all areas of the sea bed.

Artificial Intelligence Improves Environmental Best Predictions


Assimilating the potentially millions of data inputs into a useable model will require extensive computing resources. Wood is turning to artificial intelligence for some help.

"We are deeply involved in using artificial intelligence and machine learning to do predictive modeling," said Wood. "Using computer research in combination with geology and geophysics, we are able to make the best predictions we can about the environment."

NRL researchers have already demonstrated their ability to use artificial intelligence to predict seafloor properties on a global scale. Taylor Lee, a researcher on Wood's team, and Wood recently published an article in the 4 January 2019 issue of the journal *Global Biogeochemical Cycles*, highlighting their success measuring global total organic carbon. Their research pinpointed the gaps found in total organic carbon prediction, and how recent machine learning techniques relying on geophysical and geochemical properties such as seafloor biomass, porosity, and distance from the coast show promise in making comprehensive, statistically optimal predictions.

"We are at the forefront of applying machine learning in this line of research," said Wood.

Another major research challenge faced by Wood and collaborators is actual data collection. Much of the land surveying can be accomplished using satellites. The ocean floor, however, is not visible from space. The challenge only fuels Wood's naturally curious and determined personality.

"It's a lot of fun figuring out how all this stuff works" said Wood. "We have several projects using this idea, and we are almost ready to develop the model. We are successfully nowcasting various aspects of the seafloor and trying to rapidly transition research findings to the fleet." 

About the author:

Cassandra Eichner is a writer with US Naval Research Laboratory public affairs.



Naval Oceanographic Office personnel prepare to launch 10 gliders from the Pathfinder-class oceanographic survey ship USNS Maury (T-AGS 66) in the eastern Atlantic Ocean. Gliders are unmanned underwater vehicles used to collect data that is incorporated into ocean models, ultimately providing underwater forecasts for Navy operations. (Photo by Rebecca Eckhoff)

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