NAVAL SCIENCE AND TECHNOLOGY

FUTURE FORCE™

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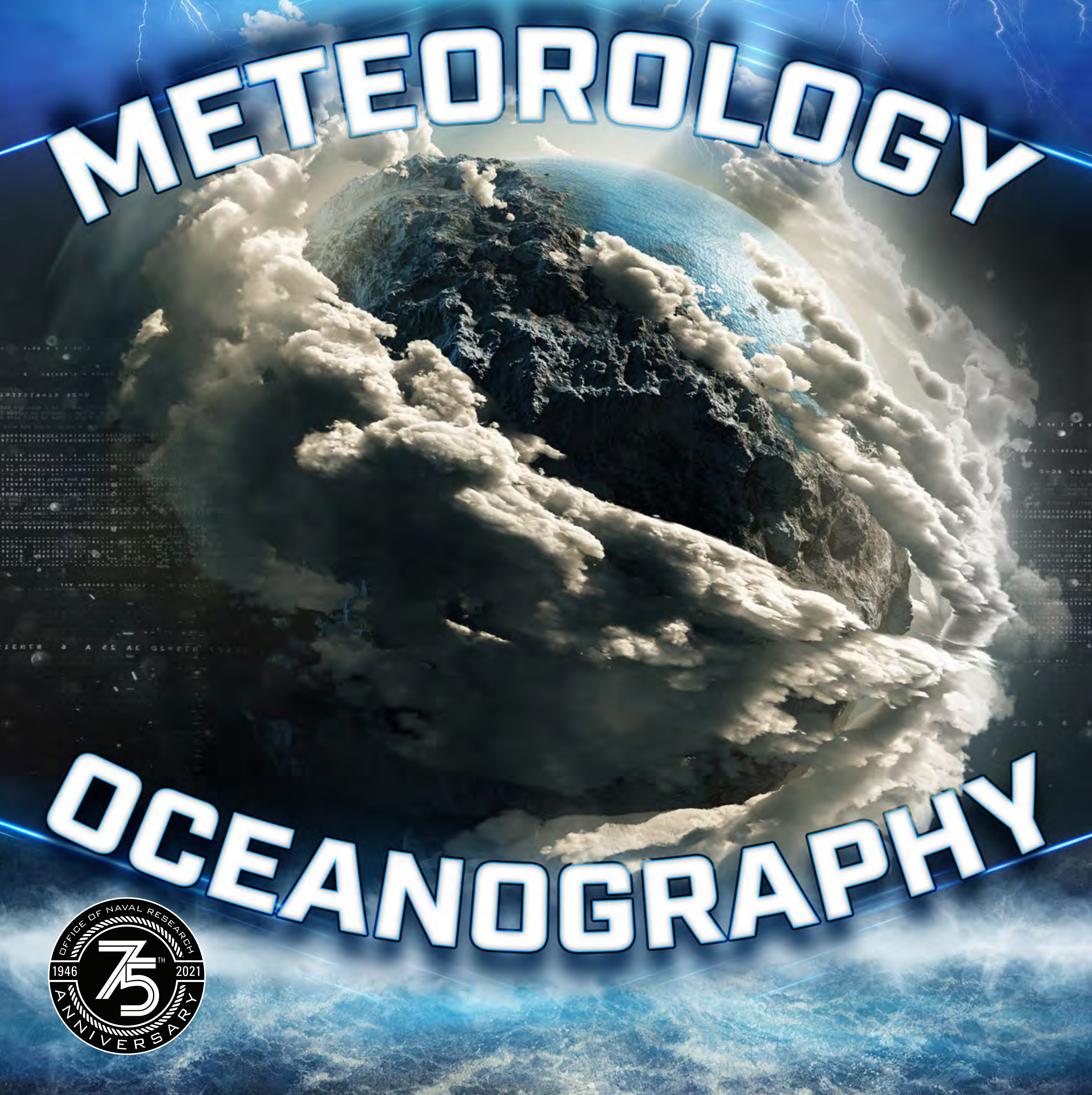
NEW BUOYS CARRY ON DECADES-LONG TRADITION OF RESEARCH

CLIMATE CHANGE DRIVES NEW DEMAND FOR OCEAN OBSERVATION

WISDOM ARMS WARFIGHTERS WITH WEATHER PREDICTION

METEOROLOGY



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IN THIS ISSUE

COLUMNS

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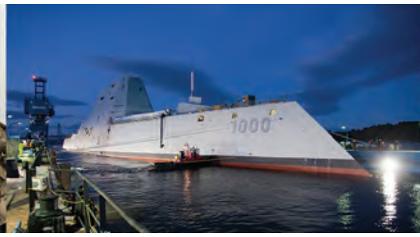

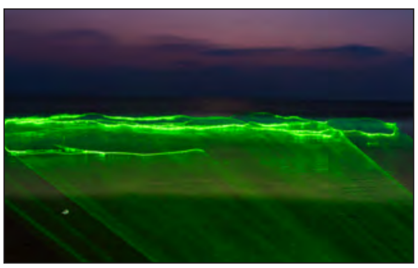

Future Force is a professional magazine of the naval science and technology community. Published quarterly by the Office of Naval Research, its purpose is to inform readers about basic and applied research and advanced technology development efforts funded by the Department of the Navy. The mission of 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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Front Cover: Illustration by Jeff Wright.

SPEAKING OF S&T

By Rear Adm. Lorin Selby, USN

Photo by MCSN Jackson Adkins

Ocean acoustic tomography. Non-GPS navigation. Weather-informed spectrum dominance. These and other topics featured in this edition of *Future Force* might not be household terms—certainly not like laser weapons or autonomous systems. But the subjects covered in this issue are ones that strike near and dear to the heart of anyone who has ever been on a submarine, surface vessel, or aircraft, civilian or military.

As a submariner, I can attest firsthand to the importance of understanding—and the unique advantages in predicting—conditions below the waves; surface warfare officers and aviators know well the importance of understanding conditions in their respective domains. Knowledge of the environment is critical for the safety of all operations, but it is also critical for tactical planning. For example, atmospheric conditions affect electromagnetic sensors such as radar and infrared systems, as well as emergent directed energy systems such as laser weapons. Likewise, ocean conditions affect the performance of sonar—our primary antisubmarine warfare tool—as well as multiple facets of mine warfare.

Understanding the environment we work in helps us maintain our tactical advantage. Better knowledge can be the difference between victory and defeat, a fact recognized and articulated by Task Force Ocean reports that have advocated for increased Navy-relevant ocean science through strengthened partnerships with academia and the private sector, a far-sighted but urgent effort that the Office of Naval Research (ONR) continues today.

Situational awareness has been critical for mariners since the first ship went to sea. For the US Navy, the work goes back almost to our roots—the Navy has been involved in the development of marine meteorology since the 1840s. Since the end of World War II, science has enlisted computers to assist with weather forecasts. The Navy realized the critical importance of the ocean's influence on the weather, and pioneered the use of "coupled" modeling—representing the influence both the sea and the air have on the development of weather.

The Navy's new Earth System Prediction Capability continues the next generation of this work, using an Earth System Model that couples interactions between atmosphere, ocean, waves, land, and sea ice. This unique system already is being used operationally by the Naval Ice Center to assess Arctic navigability and sea ice out to 45-day lead times—and has significant potential for other long-range predictions for Department of Defense decision support, as the system is typically run at much higher spatial resolutions than current climate models. The Earth System Prediction Capability might be used, for example, to generate high-fidelity predictions of the opening of new Arctic sea routes, or for typhoon activity several weeks to months before a ship transit.

These issues have never been more important. As has been widely reported, from scientific journals to Congressional testimony, the loss of polar and glacial ice, warming waters, increased drought and wildfire intensities, and slowly rising sea levels, all tell us that the Earth is changing, and there will be future challenges to negotiate, including the call for a naval response to humanitarian assistance and disaster relief efforts around the world, and new elements to consider in military operations.

The scientists and engineers sponsored by ONR, the US Naval Research Laboratory, and ONR Global, are aware of these challenges and are working hard to keep our fleet and force safe, and maintain naval dominance. They often do basic research; in truth, however, there is nothing basic in their mission. They operate at the cutting edge, breaking new ground from observational campaigns leveraging ONR's world-class research vessels and facilities, to pushing the state of the art in supercomputer-enabled numerical modeling.

I hope that as you read this edition, you understand better the challenges, and the opportunities, faced by our scientists and engineers, as well as our Sailors and Marines. Much like how the atmosphere and ocean deep are connected, so too are our warfighters and research community. Together, we will continue to press, continue to advance, and continue to win.

Rear Adm. Selby is the chief of naval research.

METEOROLOGY AND OCEANOGRAPHY

Understanding the marine environment is a strategic as well as tactical imperative for naval forces. Whether it is understanding the long-term geopolitical implications of the warming waters of the Arctic, or monitoring hour-to-hour weather forecasts for a carrier strike group in hostile territory, the sciences of meteorology and oceanography make modern naval warfare possible.

▶▶ By Colin E. Babb

DETERMINING TEMPERATURE CHANGE ON AN OCEANIC SCALE

DECADES INTO HIS CAREER AS ONE OF THE 20TH CENTURY'S MOST RENOWNED OCEANOGRAPHERS, WALTER MUNK SOUGHT TO USE SOUND TO DETERMINE THE CHANGING TEMPERATURES OF WHOLE SECTIONS OF OCEAN AT ONE OF THE WORLD'S MOST ISOLATED ISLANDS.

A lonely, windswept outcropping of rock and ice just below the region of the southern Indian Ocean that sailors call the "roaring forties," Heard Island seems an unlikely spot for a scientific experiment with global ambitions. The first person to record a sighting of the island, on a trading voyage in 1853, at first mistook it for an iceberg. Exploited for decades afterward by sealers looking for elephant seal oil, Heard Island nonetheless has a long pedigree with regard to scientific exploration: it was visited by HMS Challenger in 1874, and a German Antarctic expedition in 1902. Nearly 90 years later, it would be the site of an experiment attempting to prove the efficacy of using sound transmissions to measure temperature change over whole oceans.

Heard Island's peculiar location in the southern latitudes beneath the midpoint of the Indian Ocean, with clear lines of sound transmission by water into the Atlantic and Pacific Oceans, attracted the attention of a project headed by Scripps Oceanographic Institution oceanographer Walter Munk and supported by the Office of Naval Research in 1990. The purpose of the experiment was to demonstrate the feasibility of ocean acoustic tomography (OAT) on an ocean-wide scale. The concept behind OAT is relatively simple: sound travels at different speeds through water depending primarily on temperature (for seawater, currents and salinity have relatively minor impacts). Sound travels faster as the temperature of the water increases. If you measure the differences in time it takes for sound pulses to travel from a fixed source to a fixed receiver, this translates into observation of changes in average temperature—as well as temperature itself—within the space between the source and the receiver. The Heard Island experiment was intended to prove the feasibility of observing temperature change over a massive swath of the Indian, South Atlantic, and South Pacific basins from a single sound source located just off the island, with listening receivers located thousands of miles away—as far afield as Bermuda in the Atlantic and the West Coast of the United States in the Pacific.

Munk and Carl Wunsch, an oceanographer at the Massachusetts Institute of Technology, were the first to suggest ocean acoustic tomography as a method for observing temperature change in the oceans in 1979. At that time, climate change had been a matter of concern among scientists for several decades, but comprehensive and accurate means of measuring it were still limited. Sensors were mostly land-based, and most of these were located in the northern hemisphere. In order to add the oceans into global temperature calculations, their vastness and depth presented a number of challenges, not the least of which was the impracticality of dipping potentially hundreds of thousands of thermometers into a world ocean that averages more than 12,000 feet in depth. OAT offered a way to gain average temperature changes for enormous areas of ocean with very

Ted Birdsall during his work in 1983 at Kaneohe on the island of Oahu with John Spiesberger and Kurt Metzger. Birdsall and Metzger would be at different listening stations eight years later as participants in the Heard Island experiment. Photo by John Spiesberger

little logistical footprint. Using sound in such a way built on decades of earlier Navy-supported work that had resulted in the discovery of the sound fixing and ranging (SOFAR) channel in the oceans—establishing the theoretical basis for long-distance transmission of sound underwater—and the creation of the Sound Surveillance System (SOSUS), which provided a vast global network of undersea listening stations that could be used for OAT experiments.

An initial experiment off Bermuda in 1981 provided early confirmation that OAT was viable. Much of the major early work done on OAT, however, was by a team headed by a former graduate student of Munk's, John Spiesberger, who did the first serious work in ocean acoustic tomography during the 1980s. Supported by the Office of Naval Research, Spiesberger and two researchers from the University of Michigan, Ted Birdsall and Kurt Metzger, did the first significant experiments that tested the Munk/Wunsch theory in 1983 and 1986. Using a sound source located off the beach at Kaneohe on Oahu, Spiesberger used Navy SOSUS stations on the Pacific West Coast as receivers. They were measuring sound receptions 4,000 kilometers away; it would take 40 minutes for the transmissions to be received. Their work proved that both temperature and change could be measured.

Spiesberger's group also discovered that OAT needed to be done at much larger scales than what they had been doing to reach larger conclusions. "Monitoring the average temperature of an ocean basin is important, but not enough," they concluded in their 1992 paper. "[To] understand climate, we must map ocean temperature at scales between eddies and basins." Heard Island would be the next attempt to achieve this level of ambition.

The Heard Island experiment took place in January and February 1991, with the acoustic source located near the island on the specially chartered Navy research ship M/V Cory Chouest. Ten transducers were suspended from the vessel's distinctive midships moonpool. The day before the test was to begin, on January 25, several transmissions were sent in order to calibrate the ship's instruments. Three hours later, researchers at Bermuda in the Atlantic and Whidbey Island in the Pacific—more than 9,500 and 11,000 miles away, respectively—acknowledged that they had heard these transmissions. Originally planned for 10 days, the experiment lasted for half that, as the transducers quickly took such a beating from rough weather that by the 31st there were only two operational. A total of 35 transmissions out of a planned 80 were sent. In the end, the intended goal of measuring temperature and its change failed because the acoustic receptions were too unstable.

Afterward, during a lecture given before an audience at the University of California San Diego, Munk placed the disappointing experiment within the context of "things that one may look forward to very greatly [that] eventually happen in a very subdued way." He compared it to Sir Edmund Hilary's description of being, along with Tenzing Norgay, the first person to reach the summit of Mt. Everest: "I suddenly became aware of the fact that we were no longer going uphill."

After the partial success of Heard Island, the next major experiment to test OAT was the Acoustic Thermometry of Ocean Climate (ATOC) project, which lasted from 1996 to 2006. ATOC used a sound source located on Kauai and transmitted to various SOSUS stations in the north Pacific from California to the Aleutian Islands. The scope and persistence of the overall experiment proved that sound transmissions indeed could provide ocean temperature accurately. Today, although the original ambition to use OAT as a permanent, ongoing tool for measuring global ocean temperatures and temperature change has not been realized, it continues to be an important tool in regional studies such as in the Arctic.

The Heard Island experiment specifically, and ocean acoustic tomography more broadly, illustrate what science historian Naomi Oreskes has identified as a changing relationship between ocean scientists and their Navy benefactors. As the military's largesse in the postwar period began to fall off in the 1970s, scientists looked not only for new sources of funding, but also new ways to conceive of their projects. Investigating climate change, Oreskes argues in her book *Science on a Mission*, came to replace concern for Navy's and its focus on acoustics and antisubmarine warfare as the overarching mission for oceanographers. Though seemingly now on different paths, scientists and the Navy have been more in step with OAT nearly from the beginning: the Navy provided both the sources and receivers for most OAT experiments, and, according to Spiesberger, there are a number of technology transitions to the fleet that resulted from OAT experimentation.

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About the author:

Colin Babb is a contractor serving as the historian for the Office of Naval Research, and the managing editor of *Future Force*.

Photo by Australian Antarctic Division/Gary Miller 2008

RIDING THE WAVE

NETWORKED BUOYS ARE REDEFINING OCEAN DATA GATHERING

By Warren Duffie Jr.

A NEW GENERATION OF ONR-SPONSORED BUOYS DESIGNED FOR GLOBAL WEATHER AND WAVE FORECASTING IS CARRYING ON A TRADITION OF RESEARCH BEGUN NEARLY SIX DECADES AGO.

The orb-like object looks deceptively simple. It boasts a yellow-and-black color scheme, a plastic outer shell, and the profile of a basketball. The round item could easily be mistaken for a piece of flotsam that washed off a ship during a storm.

However, there is more under the hood, so to speak. Each sphere contains sophisticated electronics and dynamic software for collecting detailed data about weather and climate characteristics—including waves, surface winds and temperature, atmospheric pressure, and drift currents. Whether working alone or as part of a larger grid deployed throughout the ocean, these impressive pieces of technology are powering the next generation of weather-forecasting models. They are called Spotter buoys—the brainchild of Dr. Tim Janssen, CEO and co-founder of Sofar Ocean, a leading ocean data and intelligence supplier. Through the use of small drifting wave buoys, Sofar is creating the world's largest real-time, ocean sensor network to provide highly accurate marine weather information. The goal: provide detailed ocean data and analysis resulting in better weather and wave forecasts, improve efficiency for maritime shipping by creating the first dynamic ship routing solution (think Google Maps for the ocean), and deliver data to the science community to drive new insights in ocean research.

Janssen is a long-time Office of Naval Research (ONR) principal investigator who has received

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command support since 2004. ONR funded much as the foundation of Sofar's business model. (Dr. Pieter Smit, Sofar's chief scientist, is another ONR principal investigator.)

ONR also helped sponsor Sofar's deployment of 500 Spotter buoys throughout the Pacific Ocean in 2020, and is supporting the distribution of an additional 1,000 buoys in the rest of the world's oceans by the end of this year.

"The Spotter buoys are cheaper, lighter, and, because of their drifting ability, can cover larger areas of ocean than traditional stationary buoys," said Dr. Reginald Beach, a program officer in ONR's Ocean Battlespace and Expeditionary Access Department. "The ocean is massive. Collecting data at scale is a numbers game. It's much more valuable to get distributed measurements from, say, 500 different locations than from a few locations with more traditional sensor platforms.

"The Navy is obviously interested in ocean data because the ocean is its main operating space," Beach continued. "More abundant, effective ocean data allows for more accurate and precise weather forecasting, which improves naval capabilities at sea."

Sofar's client base includes shipping companies, environmental organizations, academic institutions, and government bodies such as the US Navy, Defense Advanced Research Projects Agency (DARPA), and National Oceanic and Atmospheric Administration (NOAA).

Increasing Understanding of the World's Oceans

Oceans cover most of the planet, drive weather and climate, and carry 90 percent of the world's goods. However, 80 percent of the oceans are unmapped, unobserved, and unexplored. This limits our situational awareness; obscures the interpretation of measurements; and greatly reduces our ability to forecast and predict ocean processes, surface weather, wave patterns, and climate dynamics.

Being able to predict ocean weather is vital to the Navy's global operations and the safety of ships at sea. In addition, the Navy wants to understand better the changing environment in the Arctic Ocean, where melting sea ice is opening the region to expanded maritime and naval activity.

Of particular concern are waves, tides, and currents, and how they affect naval capabilities.

"We're very interested in large swells and how they propagate," said Beach. "Questions we want to answer include how long did wind blow and how hard, did waves travel at different speeds and in what directions. Such information could help the Navy better predict the arrival of storms and increase preparation time."

Janssen concurred: "Weather and wave forecasting are of extreme naval interest. The current prediction models the Navy uses now are excellent, but they lack a lot of real-time data about sudden changes in weather patterns. I believe the Spotter buoys can fill this gap and radically improve ocean weather forecasts."

The Navy and agencies such as NOAA already use specialized buoys to gauge weather and wave variables. While effective, these buoys nonetheless are usually heavy (weighing several hundred pounds), expensive (costing more than $100,000 each), and moored to the sea bed in one spot, limiting coverage area to shallower regions near the coast and on the continental shelf.

Janssen's Spotter buoys cost less, weigh 12 pounds, and can be hand deployed from a ship or aircraft. No training or manual is needed. Users just need to remove a buoy from its box, turn on a switch, and drop it overboard. The solar-powered buoys can be moored in one spot for extended surveillance of a specific location, or allowed to drift with the currents to cover more expansive areas of ocean.

Each Spotter buoy collects detailed, real-time data on surface weather and transmits that to Sofar's cloud infrastructure—which compiles information into a proprietary marine-weather prediction model that can be incorporated into existing models overseen by the Navy, DARPA, and NOAA.

Spotters transmit their data via satellite and are connected to the Internet of Things (IoT)—meaning they are always connected to the Web and all their data is collected and available in the cloud. This means faster integration of real-time updates within forecasting models, useful for those tracking extreme weather events or needing to re-route a ship away from a storm. (IoT describes networks of physical objects embedded with sensors, software, and other technologies, in order to connect and exchange data with other devices and systems over the Internet.)

"This could be thought of as the Ocean of Things," said Janssen. "And our dynamic vessel routing application delivers capabilities similar to [web-mapping platform] Google Maps or [location-navigation app] Waze."

A Diverse Distribution Network

To distribute Spotter buoys throughout the world's oceans, Janssen and Sofar partner with hundreds of diverse international partners—including universities, nonprofits, corporations, and the US military and government agencies.

One participant is Dr. Alexander Babanin, an ocean engineering professor at the University of Melbourne in Australia. Babanin has known Janssen for many years and actually was one of the first customers to buy Spotter buoys on behalf of his university.

Over the years, Babanin and his students have deployed the buoys in the Arctic, Atlantic, Indian, and Pacific oceans.

"Spotter buoys are a game changer," said Babanin. "They're easy to deploy by hand—just turn on the switch and toss overboard—and offer amazing capacity for super-precise

Solar-powered Spotter buoys can be moored in a single location for long-duration data collection. Photo provided by Sofar Ocean

wave measurements. They also perform well in both smaller, shallow-water waves and large waves."

Babanin will soon distribute the buoys during a research trip to the Southern Ocean, which covers approximately one-sixteenth of the Earth's total ocean area. Babanin's team will study air-sea interaction in that region of the planet.

"The Southern Ocean is enormous, and its swells travel all over the world," said Babanin. "Until Sofar, there were almost no measurements of wave activity there—everything was limited to a few observation stations. The Spotter buoys create a large grid that allow for thorough sampling.

"I also have to credit ONR for these innovations," he continued. "I don't know if Sofar could have accomplished as much as they have, or as fast, without ONR's support of Tim's research."

Another vital partner in the buoy-deployment chain is ONR itself—namely, ONR Global, which is the command's international arm. ONR Global, through its International Engagement Office and science advisor program, is working to broaden Sofar's reach. ONR Global science advisors serve as liaisons between the operational fleet and the science and technology (S&T) community.

One such person is Tamara Kick, a science advisor based at US Fleet Forces Command, which is responsible for naval assets throughout the East Coast and North Atlantic Ocean. Kick is instrumental in coordinating the deployment of Spotter buoys from vessels leaving Naval Station Norfolk, Virginia, and crossing to Europe.

To date, Kick has primarily worked with Military Sealift Command, which controls replenishment and transport ships for the Navy, to deploy additional Spotters.

"My role as a science advisor is finding opportunities to connect operating naval forces with science and technology innovations," said Kick. "It is very important for the fleet to see the S&T ONR sponsors in its early stages, to see how it can potentially fit into the future ocean battlespace. Deployment of the Spotter buoys is a perfect example of this."

Building on a Rich Legacy of Wave Research

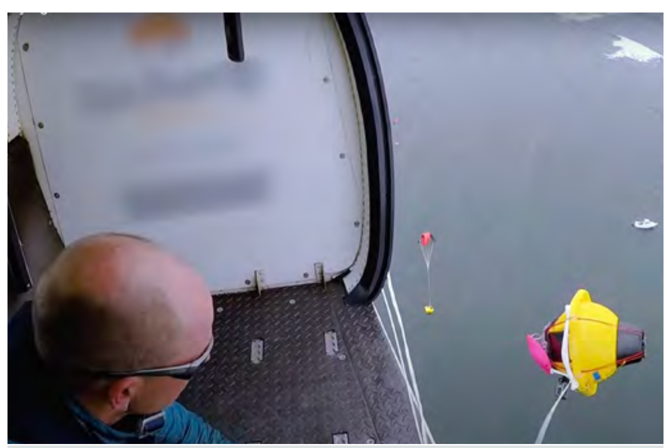
Janssen's Spotter buoy work expands on ONR's long history of studying how waves propagate, and how to incorporate that information into weather-forecasting models.

In 1963, Dr. Walter Munk—an ONR-funded oceanographer from the 1940s until his death in 2019—led a study of how swells created by Antarctic storms travel more than 9,000 miles over the Pacific Ocean before hitting the Alaskan coast. His team established observation stations in Hawaii, American Samoa, and Alaska to measure waves traveling in a circle from New Zealand to Alaska. They monitored wave pressure using sensors mounted on the ocean floor and recorded data on paper tape punched with holes.

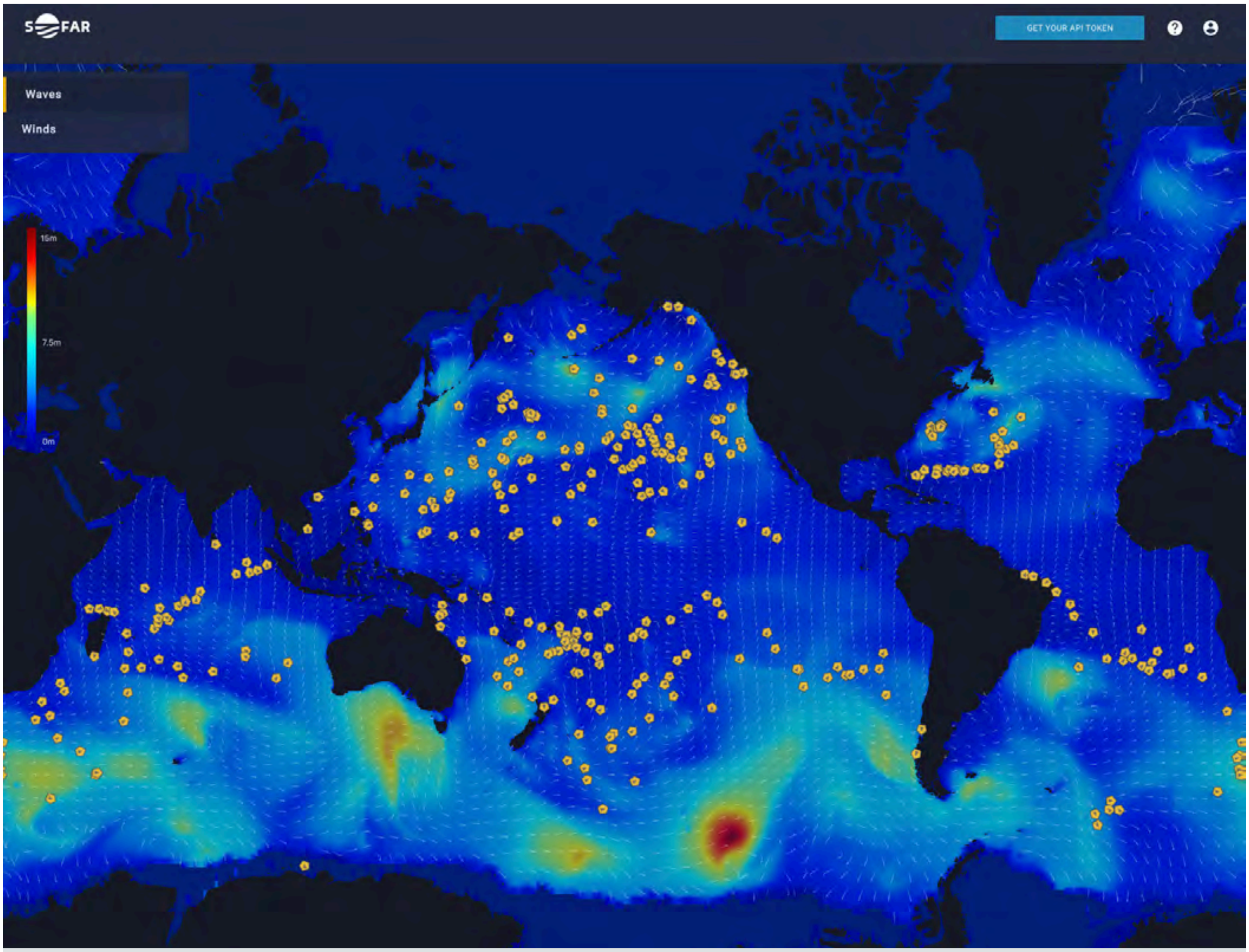
The study—known as "Waves Across the Pacific"—revealed that waves lost little energy during their trip across the Pacific. The biggest change was a shift in the observed period of the wave—i.e., the time between passing crests. The team saw that long-period traveled faster, resulting in separation (dispersion) of the wave field, with shorter-period waves arriving much later.

Munk's work provided much-needed insight into creating prediction models dealing with waves, tides and currents—and their impact on weather and naval operations.

"It was an amazing time and an exciting, important collaboration," said Dr. Klaus Hasselmann, who was a member of Munk's research team and is currently a professor at the Max Planck Institute for Meteorology in



At about 12 pounds, Spotter buoys are light enough to be deployed from either ships or aircraft and allowed to drift with ocean currents. Photo provided by Sofar Ocean



The Sofar Spotter grid, showing real-time data available at weather.sofarocean.com.

Hamburg, Germany. “ONR was one of the primary funders of the study, and has been vital to the field of wave research. Their impact on ocean research, as a whole, cannot be overstated.” (Hasselmann also knows Janssen and collaborated with him and Munk on ONR-supported wave research in the 2000s.)

“Waves Across the Pacific” was so successful in illuminating some of the mysteries of wave propagation that it inspired decades of future ONR-sponsored research. This included both the deep ocean and coastal areas affected by surrounding land masses and shifting of sediment along shorelines.

“It’s fair to say that Tim Janssen’s work with Sofar is the culmination of what Walter Munk and his team started in the 1960s,” said Beach. “It’s great to see how scientific progress and improved technology make it possible to gather wave data on such a massive scale.”

Janssen first received ONR funding in 2004, as a post-doc working for another ONR principle investigator. Within a few years, Janssen was himself a principal investigator working at San Francisco State University, where he created the first Spotter buoys. He soon launched the company that would eventually become Sofar Ocean, with ONR buying some of the first Spotter buoys available.

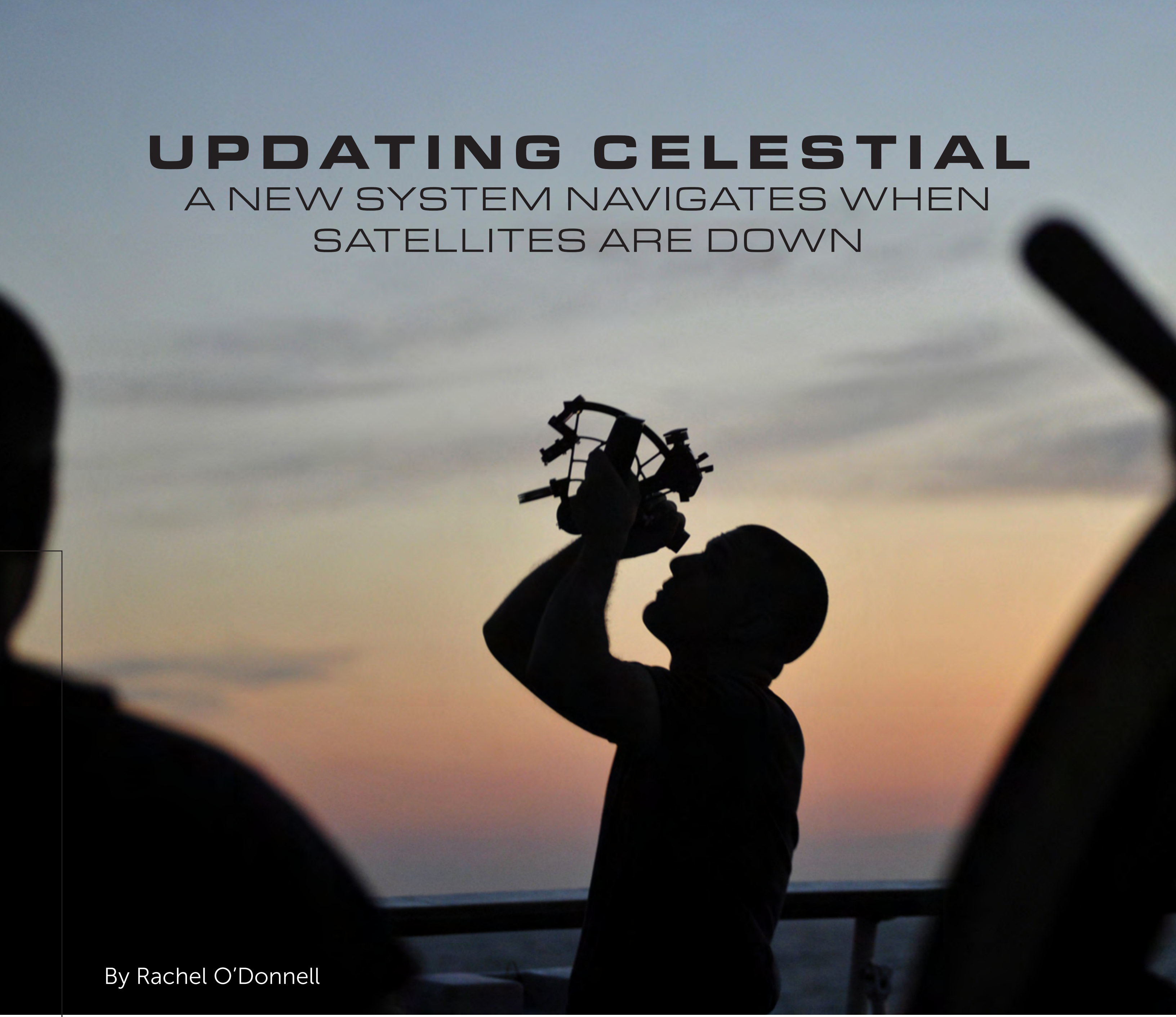
"Working with ONR has always been exceptional and highly synergistic. I believe that the shared vision on the future of distributed ocean sensing has been critical to the design and evolution of the Spotter buoys and our global network," said Janssen. "ONR's willingness to invest in innovation and be on the forefront of new ideas to increase naval capabilities is absolutely essential to deliver cutting-edge ocean research."

About the author:

Warren Duffie is the assistant editor of *Future Force*.

UPDATING CELESTIAL

A NEW SYSTEM NAVIGATES WHEN SATELLITES ARE DOWN



By Rachel O'Donnell

A PROJECT AT NAVAL SURFACE WARFARE CENTER DAHLGREN DIVISION IS LOOKING AT NEW WAYS TO USE CELESTIAL NAVIGATION WHEN GPS ISN'T AVAILABLE.

The use of the Global Positioning System (GPS) is an aspect of nearly every part of our day-to-day lives, but it has only been in the last decade that GPS has truly taken off, moving from its creation at Naval Surface Warfare Center Dahlgren Division (NSWCDD) in the late 1950s to a commercialized system used in virtually every household and situation today. Yet there are times when satellite navigation fails, because of one reason or another. For those of us using GPS in our cars, the lack of it is (usually) a simple inconvenience; for seagoing vessels, the consequences can be much more dire. That's where the Automated Celestial Navigation System (ACNS) comes into play.

"Classical celestial navigation, also known as astronavigation, is a position-fixing process that has enabled sailors to cross featureless oceans with certainty and target unsighted land with precision," said NSWCDD group lead for navigation engineering Dr. Thanh Tran.

In the past, a ship's position was determined by the navigator estimating latitude and longitude using a sextant, chronometer, and paper information. For latitude, the navigator would measure the apparent height of a celestial object above the horizon and calculate using that information and (sometimes) declination tables from a nautical almanac. Longitude

Coast Guard photo by PO2 Matthew S. Masaschi

was determined by knowing the difference between local time (usually fixed with a noon-time sextant sighting) and the time at a known point, such as at the Prime Meridian.

Following the move to digital charts and the evolution of ship navigation training and operational requirements, the Navy received recommendations to modernize the conventional celestial navigation system using techniques that are more advanced.

“The ACNS uses a computer coupled with sophisticated sensors to replace the manual operation in prediction of navigational fixes,” explained Tran. “Specifically, ACNS could continuously fix the ship’s position in both day and night with as good—if not better—accuracy than that provided by sights and calculations using a computer.”

The system is designed as an alternative solution for GPS when, for whatever reason, a connection to satellite navigation is not available.

“In the 1980s and 1990s when GPS started coming online and becoming more commercialized, systems started seeing how reliable it was and started using it themselves,” said NSWCDD senior system engineer for ACNS Huong Pham. “The satellite GPS signal is very faint and low. It can be easily interfered with—for example, when driving near a building in a city or if the weather is bad. So how can you continue to operate when you’re losing signal? You need an alternative positioning source as a backup.”

Sailors still learn traditional celestial navigation. The Automated Celestial Navigation System merges this venerable technique with modern electronics. Photo by Lt. j.g. Alexander Fairbanks

The Automated Celestial Navigation System was put to the test during Hurricane Sally, which made landfall in Alabama in September 2020. The system was aboard R/V *Point Sur* for at-sea testing at the time.

The Combat Control and Interoperability Engineering Division at NSWCDD works to integrate the ACNS project with the other combat system navigation elements. System integration is occurring in two phases, according to Pham, with the goal of having ACNS available on ships by 2023.

The system is being trialed in a program called ACNS21, which is a nonpermanent change ship installation for a 12- to 16-month period.

“The ACNS21 will take all necessary field data in real-life operation for later data analysis and system performance verification and validation,” said Tran.

ACNS21 uses the system’s camera to spot resident space objects (RSOs) – like satellites and space debris – and stars in space, and depends on when these celestial bodies are sighted to generate a navigational fix.

“ACNS doesn’t look into deep space. The system looks for stars [and other RSOs] with certain levels of brightness and precision to help calculate positioning,” said Pham.

In the second phase, ACNS will be permanently installed on additional ships.

“The use of ACNS support increases readiness in the naval surface force, making ships more self-sufficient in the event of potential GPS disruption,” said Tran. “Working on this ACNS at Dahlgren proves one more time that we always strive to support the Navy missions with innovation and advanced technologies.”

About the author:

Rachel O’Donnell is a communications specialist working in the public affairs office at Naval Surface Warfare Center Dahlgren Division.

UNMANNED VEHICLES HELP SCIENTISTS REDISCOVER THE ARCTIC

By Capt. Edward Lundquist, USN (Ret.)

AS INTEREST IN THE ARCTIC HEATS UP AFTER A DECADES-LONG HIATUS, SCIENTISTS FIND THE ENVIRONMENT HAS CHANGED.

As we see the Arctic ice diminishing, interest in the region—whether for defense, commerce, fishing, or tourism—is growing. The once foreboding icy high north now seems to be extending a "warm" welcome to people.

The US Navy and its NATO allies have long viewed the Arctic as a potential battlefield, especially for nuclear-powered submarines that can safely and covertly maneuver under the ice for extended periods of time. Operating friendly submarines, and looking for an often hidden enemy, requires a foundational knowledge of the environment and how the dynamics work. During the Cold War, much research was conducted for that reason.

When the Cold War ended, the need to operate in the far north lessened. The research was reduced. Now, some 30 years later, relations between Russia and NATO have turned cold again. As scientists return once again to measure the ice, atmosphere, and ocean, they have been startled to find that the knowledge they had collected and analyzed in the past was no longer indicative of the Arctic of today.

According to the Navy's Strategic Outlook for the Arctic, issued in January 2019, "Current scientific evidence indicates the character of Arctic continues to change. The composition of the sea ice is trending thinner and younger and sea ice coverage is still decreasing. Though sea ice extent has declined at a rate of 13% per decade in the summer and 3% per decade in the winter, understanding and accurately predicting both the inter-annual variability and regional ice coverage remains challenging."

The Cold War physics models for ambient noise, currents, and salinity that were so painstakingly developed and faithfully predicted acoustic properties for sonar are no longer valid. That means much data needs to be updated, and much about the dynamics has to be learned all over again.

"The environment is changing for anyone using underwater sound, whether it's for navigation, communications, sensing marine mammals; it's dramatically changing the way we can do things," said Dr. Henrik Schmidt of the Massachusetts Institute of Technology (MIT). "That's one reason why scientists and navies are interested again. Someone with very quiet submarines and a thorough knowledge of the Arctic Ocean and the sound propagation properties can have a significant tactical and strategic advantage."

Schmidt said he has been going to the Arctic since the 1980s, operating from ice camps and doing underwater research, particularly in relation to underwater sounds, ambient noise, and the propagation of sound. He is well grounded in the environmental conditions then, and now.

"After the Soviet Union broke up, people said, 'Wow, we don't need to do anything up there anymore. It's too expensive and the Russians are not a threat anymore.' With the ice melting, there is a focus once again on the Arctic, especially the economic interest because we now get access to resources that we haven't had before. But, as a result, we have lost two decades—or more—of effort in underwater acoustics," Schmidt said.

WE HAVE LOST TWO DECADES—OR MORE—OF EFFORT IN UNDERWATER ACOUSTICS.

As scientists come back to the Arctic, they have found that much of what they knew from before has changed. "It's very, very different from what we saw when we were last up there back in the late 80s and early 90s. We have a general science objective, but it is also significant to naval operations," said Schmidt, whose work is supported primarily by the Office of Naval Research.

There are many ways to collect data about the high north, including in-situ sensors, aircraft, satellites, ice stations, and research ships. Regardless of the method, however, collecting data in the polar regions is hard.

According to Dr. Neil Barton, global modeling section meteorologist at the US Naval Research Laboratory Marine Meteorology Division in Monterey, California, the main challenge in modeling the earth system in the extreme poleward latitudes is the scarcity of

The crew of USS *Connecticut* (SSN 22) enjoys ice liberty after surfacing in the Arctic Circle during Ice Exercise 2020. Photo by MC1 Michael B. Zingaro

Photo by MC1 Michael B. Zingaro

observations to initialize and diagnose their models. “Obtaining and maintaining in situ observations is difficult because of harsh conditions,” he said. “In addition, many satellite observations have more difficulties observing meteorological and ocean conditions compared to lower latitudes due to the cold surface, a surface with a high albedo (referring to how much radiation from the sun is reflected or absorbed by the surface), and low amounts of moisture in the atmosphere.”

Barton said the scarcity of observations corresponds with higher uncertainty in the observations. “In addition to observation scarcity, the surface processes at the polar latitudes are complex due to the tight connection between the ocean, sea ice, and atmosphere. Changes in the sea ice are greatly related to changes in the atmosphere and ocean.”

One way to gather data and build experience in the region is the Navy’s biennial Ice Exercise (ICEX), which provides an opportunity for the military, academia, industry, partner nations, and other agencies and organizations to collect meteorological and oceanographic data on, above, and under the Arctic Ocean. A major feature of these exercises is the building of a temporary camp on the ice, which is usually visited of one or more submarines. ICEX 2020 included a series of experiments that have been built on previous testing, which involves the precise navigation of underwater vehicles operating under the ice. One of the important tools for underwater sensing, construction, and warfighting is unmanned underwater vehicles (UUVs), which can conduct missions that are impractical otherwise. Some of the data cannot be gathered any other way, and is critical to understanding better the long-term environmental changes in the air, ice coverage, and throughout the entire water column.

Divers from USS *Seadragon* (SSN 584) prepare to explore under the North Pole in September 1960, taking the first photographs made of the underside of the Arctic ice.

THE QUALITY OF SCIENCE CONDUCTED AT ICEX IS PRETTY REVOLUTIONARY.

This is why researchers from the Laboratory for Autonomous Marine Sensing Systems at MIT, the Navy’s Arctic Submarine Laboratory, Unmanned Undersea Vehicle Squadron (UUVRON) 1, and General Dynamics Mission Systems Bluefin Robotics brought MIT’s MACRURA unmanned underwater vehicle to ICEX 2020 to refine navigation capability and improve situational awareness to understand the Arctic undersea environment better, and how is it different from what it was the 1990s.

“Some of the data collected and reported by autonomous systems cannot be gathered any other way," said Schmidt, "and it helps us better understand the long-term environmental changes in the air, ice coverage, and throughout the entire water column."

In most ocean environments, the water temperatures are warmest at the surface, and decrease as a function of depth. Sometimes there are layers, channels and currents, all of which affect sound energy and thus sonar performance.

Because the below-zero air was much colder than the sea water, the ocean would have “heat drops” from the water to the atmosphere. “And what that created was a temperature profile where you have the temperature decreasing towards the surface,” said Schmidt.

Today, the water temperatures at different depths have changed, so the sound propagation profiles are different, too. That means layers and channels that could be used in the past to detect and track submarines are no longer there, or have changed. In addition, what was formerly solid ice is now much more dynamic.

“We compared the ambient noise—the noise created by the ice—that we got back in 1994 with what we got in 2016 and 2020, at the same location and same time of year,” said Schmidt. “The sources of the sound have changed. We used to have four-meter-thick pack ice when we were up there back in the 90s, and most of the noise was created by these ice floes grinding against each other. The ice would fracture, but not break. Today the ice is thinner, and when stressors develop because of wind and current, then the ice breaks. So not only did we see that sound propagating differently because of this oceanographic feature, but also the ambient noise is dramatically changed because of the much thinner ice. Today we have a lot of noise in the Arctic, generated by ice fracturing and ice floes grinding against each other.”

However, operating UUVs under the ice poses challenges of its own. To begin with, launch and recovery of the vehicles can be tricky. In thick ice, it is

Partner nations' flags fly over Ice Camp Seadragon during ICEX 2020. Photo by MC1 Michael B. Zingaro

especially challenging. The team had to cut a "hydro hole" three feet wide and 15 feet long in the six-foot-thick ice, removing eight tons of ice to make a hole large enough to place MACRURA in the water.

One of the limitations in the high north is the lack of land-based communications or satellite coverage. Most UUV operations occur in open water, with direct communications by means of acoustics or surfacing and transmitting over a data link to the host platform or satellite. GPS provides precise position updates, so the vehicle knows where it has been, and it can mark a precise location for anything it has found. When operating under the ice, however, getting a GPS update can be problematic.

The precise position is important not only so the vehicle can return after a mission, but so that anything it has detected or observed can be reported with an accurate fixed location to provide appropriate context.

"We can drill a hole in the ice and drop in an ice-tethered profiler that's anchored in the surface ice and has a suspended sensor below at predetermined depths that measures temperature and salinity versus depth. We can also attach modems to the tether that can communicate with a UUV," said Schmidt.

The team developed an experiment involving an integrated communication and navigation-aiding framework known as ICEX tracking range—or icex-tracker. The experiment used a network of surface buoys equipped with small acoustic modems suspended beneath the ice that were linked by radio communications to the ICEX base camp, Camp Seadragon. Submarines coming to the surface next to the camp used the buoys for positioning.

As a crewmember aboard USS *Connecticut* (SSN 22), Lt. Cmdr. Dan Goodwin went up to the Arctic for ICEX 2018. A year later, he was selected for a graduate program jointly run by MIT and Woods Hole Oceanography Institution in 2019, where he became part of Schmidt's ICEX team, and found himself back in the Arctic and running experiments from Camp Seadragon.

"Our submarines use inertial navigation systems so they know where they are when submerged," said Goodwin. "But subs need to get periodic updates, such as a GPS fix from a satellite. The same applies to UUVs."

Based on GPS satellite orbital inclinations, the 2020 Camp Seadragon was not so far north so as to completely lose GPS, but the GPS satellites don't pass overhead above the Arctic Circle, so a fix is dependent on fewer satellites than normal.

"INS [inertial navigation system] is very good at speed, heading, and pitch and roll, but sometimes you need something else to give a more precise location," said Goodwin. "For our unmanned vehicles, we normally use a doppler velocity log [DVR] for measuring speed over ground but the sea floor is still far away in most cases up in the Arctic unless you're really close to the coast, so that was not an option. We reversed the DVR so it was pointing up to measure speed under the ice above. However, the ice is not fixed—it's moving, too. The ice may only be moving at a knot—while the vehicle is operating at three or four knots—but that's not insignificant compared to the speed of the vehicle. There are currents, too, that may or may not be moving in the same direction as the ice. So, eventually we have some drift in the location of the vehicle."

To help submarines safely surface next to the camp, a pattern of tethered communications modems is suspended under the ice.

"For ICEX 2020, our science team experimented with MIT's MACRURA, which is a General Dynamics Missions Systems' Bluefin-21 UUV, to navigate precisely while conducting a submerged mission," Goodwin said. "We used four buoys about 2,000 meters apart, the same buoys that the submarines used, with micro modems at both 30- and 100-meters depths to compensate for the temperature and salinity differences in the water that affect acoustic propagation. This allowed the UUV to adaptively switch between modems depending of the depth of the vehicle to ensure the most coherent acoustic communication. The travel time of those signals provided acoustic aided navigation for the UUV. The system was also able to compensate for currents, which can vary in in direction and intensity at different depths."

According to Goodwin, the system is completely scalable. "We could use more buoys to provide wider coverage, and provide positioning to all types of UUVs."

"The quality of science conducted at ICEX is pretty revolutionary," said Goodwin. "We were able to demonstrate under-ice navigation to near-GPS quality. The MACRURA vehicle knew where it was, and we knew where it was. When we had an issue, we were able to go directly to where it was, cut a hole in the ice, and extract the vehicle."

About the author:

Capt. Lundquist writes on naval, maritime, and defense issues, including developing science and technology for warfighters.

MINUS 27 DEGREES: PERFECT FOR POLAR RESEARCH

The Navy's biennial ICEX in the Arctic Ocean is more than a demonstration of its ability to operate in the extreme latitudes—it's also a unique opportunity to do science.

Led by Commander, Submarine Forces, ICEX 2020 brought together various Navy commands and activities, other services, allies, and partner nations to enhance collective abilities to operate in the harsh polar environment.

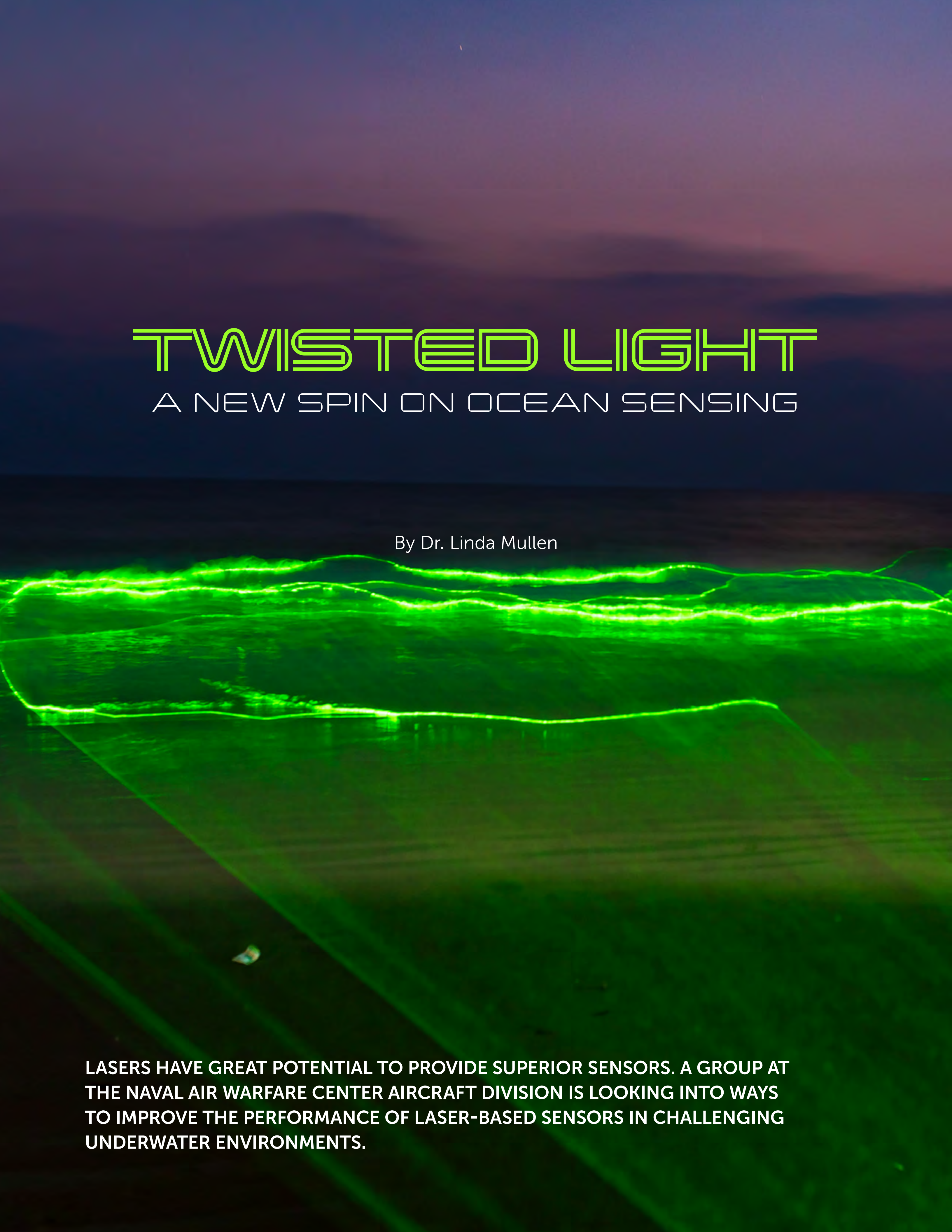
The Navy's Arctic Submarine Laboratory in San Diego led the coordination, planning, and execution for the three-week exercise in March 2020 involving five nations, two submarines, and more than 100 participants at the ice camp (not counting the submarine crews). The Bremerton, Washington, based USS *Connecticut* (SSN 22) and the Groton, Connecticut-based USS *Toledo* (SSN 769) conducted multiple Arctic transits, a North Pole surfacing, and other training evolutions while in the Arctic Ocean. The submarines surfaced next to Camp Seadragon, a temporary outpost constructed on an Arctic ice floe 200 miles north of the Alaska coast in the Beaufort Sea. Named for the attack submarine USS *Seadragon* (SSN 584), which helped pioneer navigation in and under the Arctic Ocean in the 1960s, the temporary camp provided a stable platform for the command-and-control center, tracking range, sensors, communication equipment, and facilities for 45 personnel at a time, who were responsible for the submarine operations and under-ice navigation exercises.

Preparation for the event begins years in advance from building an operational plan with research goals to the months before tracking ice floes with satellite imagery to determine which multiyear ice floe is best to support building the ice-camp. Once some tentative areas were identified, flights out of Prudhoe Bay, Alaska, were conducted to determine feasibility of the camp.

The high north is a foreboding environment. Even as the climate is changing, and the multiyear Arctic ice cover is diminishing, there is still plenty of ice, making it inaccessible for much of the year. But there is more seasonally open water now, and that is inviting commerce, resource exploitation, and tourists. Travelling from Asia to Europe by the polar route is much shorter, and in shipping, time is money.

"The Arctic is a potential strategic corridor - between Indo-Pacific, Europe, and the US homeland—for expanded competition," said Vice Adm. Daryl Caudle, Commander, Submarine Forces. "The Submarine Force must maintain readiness by exercising in Arctic conditions to ensure they can protect national security interests and maintain favorable balances of power in the Indo-Pacific and Europe if called upon. ICEX 2020 provides the opportunity for the Submarine Force to demonstrate combat and tactical readiness for sustained Arctic operations in the unique and challenging Arctic environment."

Shutterstock photo by Pranay Chandra Singh



TWISTED LIGHT

A NEW SPIN ON OCEAN SENSING

By Dr. Linda Mullen

LASERS HAVE GREAT POTENTIAL TO PROVIDE SUPERIOR SENSORS. A GROUP AT THE NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION IS LOOKING INTO WAYS TO IMPROVE THE PERFORMANCE OF LASER-BASED SENSORS IN CHALLENGING UNDERWATER ENVIRONMENTS.

The advantages of using laser-based sensors to probe the subsea environment include their ability to penetrate the air/sea boundary and their potential to generate high-resolution images needed for object identification. The performance of laser systems in water, however, is adversely affected by absorption and scattering. The fact that the color of the world's oceans varies from green in coastal regions to blue in deep water is evidence that the spectral components of sunlight are absorbed differently because of the water's constituents.

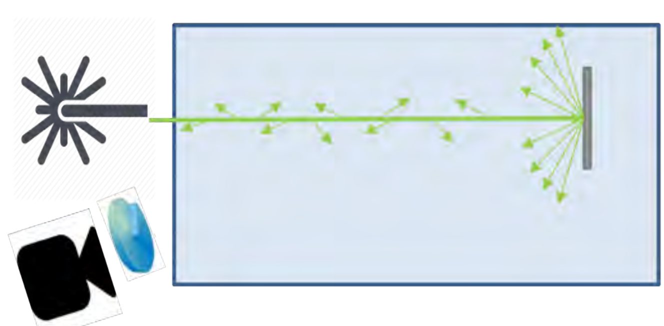
A laser's wavelength can be tailored to match the hue of the water to maximize depth penetration, but scattering of a laser by organic and inorganic particles can degrade sensor performance. Scattering produces a "headlight in fog" effect by scattering light back to the receiver that clouds the presence of objects in the scene. Scattering also causes an otherwise collimated (or directional) beam of light to expand and produce image blurring and loss of image contrast. Simply increasing laser power does not improve sensor performance since both scattered light and nonscattered light increase proportionally with laser power. Instead, a method to suppress scattered light must be developed to enhance laser imaging in highly scattering environments.

A previous *Future Force* article, "Carrying Radar Signals with Light" (Winter 2016), detailed a technique that researchers at the Naval Air Warfare Center Aircraft Division developed that uses radar-encoded lasers to reduce the negative effects of scattering on underwater laser imaging system performance. This approach relies on the ability of a laser's intensity to be varied quickly in time, creating a beacon that a receiver can lock on to and reject light that has scattered multiple times. An improvement in sensitivity is achieved when the signal reflected from the object retains the radar encoding and can be processed with well-established radar signal processing techniques.

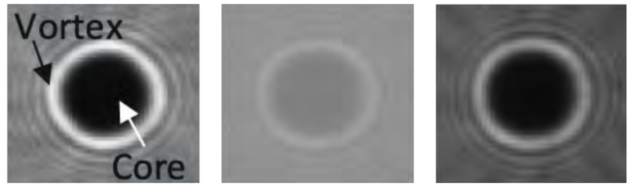
The Naval Air Warfare Center team has recently discovered that encoding the spatial properties of laser beams provides another way to separate scattered and nonscattered light. Twisted light, or light with orbital angular momentum (OAM), is characterized by a phase that "spins" around the beam's propagation axis. This twisting of the laser wavefront produces a donut-shaped intensity pattern, or vortex, with a central dark region. One method used to encode a laser beam with OAM is to pass it through a phase plate where the thickness of the plate changes in a spiral pattern resembling a spiral staircase. While this method requires a different device for each OAM mode, a spatial light modulator can be programmed to generate a variety of modes using a single device. Regardless of how the twisted light is created, beams with OAM have been used to trap and manipulate microscopic particles (optical tweezers), increase the bandwidth of optical communication links, and support novel remote sensing applications.

Researchers at the Naval Air Warfare Center are investigating remote sensing applications of twisted light by exploiting the fact that only coherent, nonscattered light can be encoded with OAM. In a recent patent by the group, "Optical Detection of an Object in a Turbid Medium Using an Optical Vortex" (US Patent No. 10,725,154 B2, July 28, 2020), a technique is described where a phase plate is used as a "coherence filter" in front of a camera that views an underwater scene (see Figure 1). When a colocated laser is aimed at an object, the light reflected from the object (nonscattered light) and the light scattered by the water (scattered light) passes through the phase plate before reaching the camera. The key is that only the nonscattered light forms a vortex and creates a "donut" intensity pattern on the camera (Figure 2a). The scattered light does not form a vortex and is distributed randomly across the camera aperture (Figure 2b). When the signal collected in the donut "core" is subtracted from the signal collected in the vortex ring, the nonscattered signal remains (Figure 2c). Therefore, a weak, nonscattered return from an object can be distinguished from the large, scattered return from the environment, which significantly improves the sensitivity of a laser sensor operating in murky water environments.

The research group has collaborated with partners in academia to demonstrate the effectiveness of the "optical vortex" approach in laboratory water tank experiments. A paper in the 22 May 2017 volume of the *Proceedings of SPIE* documents the results of tank experiments showing how the return from an object was extracted even when its amplitude was several orders of magnitude below the signal scattered from the environment. This work was completed as part of a collaboration with the Micro-Photonics Laboratory at Clemson University which created the phase plates used in the experiments. An article in the 5 February 2018 *Optics Express* describes similar experiments conducted as part of a collaboration with Clarkson University. In this work, a pulsed laser and a high-speed camera were used to resolve the return signals in both space and time. The results showed that not only did the use of a phase plate help detect a weak object return that would otherwise be obscured by scattered light, but it also improved the accuracy of the measured object range.



A laser illuminates an underwater object that scatters light to a camera colocated with the illuminator. A phase plate is used as a coherence filter in front of the camera to separate scattered and nonscattered light.



Images collected by the laser sensor in Figure 1 in clear water (a) and turbid, murky water (b). When the signal in the core is subtracted from the signal in the vortex, the scattered light is removed (c).

The success of using the properties of OAM to improve the detection of objects in highly scattering environments inspired the Naval Air Warfare Center group to investigate other uses of twisted light for maritime sensing. The team turned to the optical ground truthing measurements needed to obtain accurate predictions of laser sensor performance in different underwater environments. One of the key measurements is the beam attenuation coefficient, which is the sum of the effects of scattering and absorption on the transmission of light in water. Since the beam attenuation coefficient is the combined loss due to absorption and scattering, only nonscattered, unabsorbed light must be detected when measuring the amount of light transmitted through a volume of water. Several commercial transmissometers are available to measure the beam attenuation coefficient in situ, but the accuracy is limited in murky water because of the fact that scattered light cannot be completely eliminated from the transmission measurement.

The Naval Air Warfare Center team recently patented an idea using OAM to improve the accuracy of transmissometer measurements ("Optical Vortex Transmissometer" [US Patent No. 10,871,445 B2, December 22, 2020]). The concept is to use the same phase plate coherence filter in front of the optical receiver to eliminate scattered light from the transmission measurement. By subtracting the average core intensity from the average vortex intensity, only the nonscattered, unabsorbed light is used to compute the beam attenuation coefficient. The team published a paper in the May 2018 *Proceedings of SPIE* to document the results of laboratory water tank experiments completed to test the improved transmissometer concept.

The results showed that measurements obtained by a commercial transmissometer instrument under predicted the beam attenuation coefficient at high scattering concentrations caused by the collection of scattered light. The optical vortex transmissometer, however, produced beam attenuation values that were linear with scattering concentration and were therefore more accurate than those obtained with the commercial instrument. Improving the accuracy of ground-truthing measurements, such as the beam attenuation coefficient, that are used as inputs to performance prediction models will directly affect the accuracy of those models in assessing sensor performance in different operational environments.

Future directions for the twisted light research include combining spatial and temporal encoding of light to further enhance sensor performance. By encoding light with both radar information and OAM, the benefits of each approach can be leveraged to reduce the contribution of scattered light in optical sensor measurements. A focus will be to implement this combined encoding scheme for optical imaging where high resolution is needed in both space and range to create high-quality, three-dimensional images for identifying challenging underwater threats. Another future research area is to extract information about the underwater environment from the recovered spatially encoded signal. By transmitting OAM beams with different amounts of "twistedness," the team is investigating whether the transmission of different OAM orders is dependent on the environment and whether those dependencies can be exploited to extract information about the environment. Such information can be related to optical ground-truthing measurements to predict sensor performance or be used to sense changes in the underwater environment caused by the presence of localized threats.

As evidence of OAM's potential for use in remote sensing, the Office of Naval Research has sponsored two Multidisciplinary University Research Initiatives in topic areas associated with OAM. The first will investigate light/matter interaction in maritime environments due to dynamic orbital and spin angular momentum states, in both linear and nonlinear regimes. This basic research will lead to new ways to exploit spatially encoded beams based on the underlying physics. The team is led by Clemson University, and includes researchers from the University of Central Florida, University of Southern California, University of Rochester, Duke University, and University of North Carolina at Charlotte. The second initiative, led by Boston University, also considers the light/matter interaction with spatially encoded beams. It is anticipated that this effort will lead to novel ways of generating and detecting OAM beams for practical sensing applications.

The use of twisted light for both above water and below water applications is growing. Strategic collaborations with academia continue to be important for leveraging state of the art research and directing it toward important Navy applications. By establishing a knowledge base and a capacity for twisted light research, the Naval Air Warfare Center Aircraft Division team is positioned to address a wide variety of oceanographic applications and impact current and future Navy capabilities.

About the author:

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CLIMATE CHANGE DRIVES NEW DEMAND FOR OCEAN OBSERVATION

By Lt. Cmdr. U.H. Jack Rowley, USN (Ret.)

WITH CLIMATE CHANGE INCREASINGLY SEEN AS A NATIONAL SECURITY ISSUE, THE US NAVY AND NOAA ARE PARTNERING TO SHARE THEIR DATA ON THE OCEANS. TO MEET THE NEED FOR BETTER OCEAN OBSERVATION, RELIABLE UNMANNED SENSOR PLATFORMS HAVE BECOME MORE IMPORTANT THAN EVER.

A number of streams have come together in 2021. Collectively, they highlight the continuing importance of comprehensive ocean observation to the nation and the Navy. Importantly, there are new, innovative ways and means that this real-time cataloging of oceanic phenomena can be conducted reliably and repeatedly and at relatively low cost.

The media have been well-populated with stories noting that climate change is now a national security priority. The new administration has been explicit that it will implement this imperative, noting that "the Pentagon will include climate change-related issues in its National Defense Strategy."[1]

An important aspect of dealing with climate change is ocean observation. This is one of the reasons that two major ocean stakeholders, the US Navy and NOAA, have signed an agreement to collaborate on ocean observation, data collection, and analysis.

This Navy-NOAA initiative includes plans to expand the development, acquisition, fielding, and operation of unmanned maritime systems in the nation's coastal waters as well as in world's ocean waters.[2] This opportunity has only become possible because of the rapid development of unmanned maritime systems that can be fitted with sensors to measure ocean phenomena accurately and comprehensively and then communicate this information to land-based sites.

These trends presage a new era in ocean observation that will lead to comprehensive data collection to support global Navy and Marine Corps operations. By enabling scientists to make data-driven decisions based on the health of the oceans and the atmosphere, this effort will help stakeholders compile the data that are crucial to addressing the national security threat of climate change.

A National Security Imperative

In 2021, Secretary of Defense Lloyd Austin made it clear that climate change is a clear and present danger: "The Department will immediately take appropriate policy actions to prioritize climate change considerations in our activities and risk assessments to mitigate this driver of insecurity." Austin went on to say:

> As a leader in the interagency, the Department of Defense will also support incorporating climate risk analysis into modeling, simulation, wargaming, analysis, and the next National Defense Strategy. And by changing how we approach our own carbon footprint, the Department can also be a platform for positive change, spurring the development of climate-friendly technologies at scale.[3]

To address climate change at the national level, a wide array of federal, state, and local officials recognize that they must make decisions based on data, not conjecture. Making these data-driven decisions depends on collecting the right data, at the right place, at the right time. This is not a trivial undertaking, and in a budget-constrained environment, having various agencies collect—but fail to share—ocean data is a recipe for failure.

In addition, anecdotal evidence suggests that where those with stewardship for various aspects of ocean sustainment cannot find an affordable way to collect this data, it will simply not be obtained. These gaps lead to an incomplete picture of the ocean's health, and with it, suboptimal solutions to achieving long-term ocean sustainment—including dealing with climate change.

A Partnership to Collect Oceanic Data

One of the reasons for the Navy-NOAA partnership is that by working together, NOAA will be able to leverage the Navy's expertise, infrastructure, best practices, and training to accelerate its science, service, and stewardship missions, especially its efforts to address climate change. The Navy's executive agent and key stakeholder in this effort is the Naval Meteorology and Oceanography Command.

The command's mission is to define the physical environment from the bottom of the ocean to the stars to ensure the Navy has freedom of action to deter aggression, maintain freedom of the seas, and win wars. In addition, Naval Oceanography has been a global pioneer in the development and use of unmanned systems.

Rear Adm. John Okon, Commander, Naval Meteorology and Oceanography Command, emphasized why this partnership is important when he noted upon the signing of the agreement that it "lays the foundation for collaboration, engagement, and coordination between NOAA and the U.S. Navy that our nation has never seen before. It will help us take advantage of each other's strengths to advance each of our strategic and operational mission priorities."[4]

NOAA conducts research and gathers data about the global ocean and atmosphere to forecast weather, predict climate, protect the ocean, and sustainably manage marine resources. These missions rely on a continuous process of testing and evaluation of new technologies such as unmanned systems to improve data gathering.

Retired Navy Rear Adm. Tim Gallaudet, Assistant Secretary of Commerce for Oceans and Atmosphere and deputy NOAA administrator, emphasized the importance of this partnership, "With the strengthening of our ongoing partnership with the Navy, NOAA will be better positioned to transition unmanned maritime technologies into operational platforms that will gather critical environmental data that will help grow the American Blue Economy."[5]

The Navy-NOAA partnership is a natural outcome, given the similar roles of both organizations. Here is how Charles Alexander, chief of the planning and performance management division at the NOAA Office of Marine and Aviation Operations, put it:

> The Navy has significant capacity for testing and evaluating marine unmanned systems. We intend to collaborate with the Navy on doing that on their test ranges and their facilities. The Gulf of Mexico is a good example.[6]

The pact formalizes the Commercial Engagement through Ocean Technology Act of 2018 that formalizes the already-in-place work that the Navy and NOAA have been doing to leverage emerging unmanned technologies.[7]

Active and Disciplined Experimentation

An important goal of the Navy-NOAA partnership is to enhance the ability of both organizations to conduct data collection. This is critical to ensuring that the fleet and force have the right oceanographic and metrological information at the tactical edge. This "Emerging Power of Data" was identified in the 2018 Office of Naval Research document, A Framework for Accelerating to the Navy and Marine Corps after Next, which noted:

> Data is trending towards universal collection on a continuous basis. Amassing, sharing and understanding vast data offers great potential. Advances in data collection, storage and analytics, computing devices, networking, and autonomous processing and decision-making are disruptive, but also offer advantages.

Much of this same data collected to support the operating forces is also essential to help assess the health and vitality of the world's oceans as well as the ability to make data-driven decisions to combat climate change. For both the Navy and NOAA, a major appeal of unmanned systems is to provide a persistent sensor picture for areas of interest.

The high cost of using manned air or sea craft to conduct these observations is driving this move to unmanned maritime systems. Add to this the dangers of using these vessels in bad weather, in turbulent waters, or at night. Given the totality of these factors, using affordable unmanned surface vehicles to conduct these observations has a strong appeal to a wide array of stakeholders.

The Office of Naval Research and the US Naval Research Laboratory (NRL) Ocean Sciences Division at Stennis Space Center, Mississippi, have a strong stewardship

A MANTAS unmanned surface vehicle conducted nearshore scanning. Photo by Maritime Tactical Systems, Inc.

Photo by MC2 Justin Daniel Rankin

role in marshaling various agencies—both inside and outside of government—to lead a broad effort to connect scientific discovery with civilian industry and universities across the nation and beyond. That is why NRL has joined the Naval Surface Warfare Center Panama City Division and the Naval Meteorology and Oceanography Command to form the new Gulf Coast Tech Bridge, which spans four states—Florida, Alabama, Mississippi, and Louisiana.

This Navy effort is aligned with the NOAA Unmanned Systems Strategy: Maximizing Value for Science-based Mission Support, which highlights how NOAA intends to leverage unmanned systems to support ocean observation: "The purpose of the National Oceanic and Atmospheric Administration Unmanned Systems Strategy is to dramatically expand the collection and utilization of critical, high accuracy, and time-sensitive data by increasing the application and use of unmanned aircraft and marine systems."

The Navy and NOAA agreed to move out rapidly in an effort to experiment with ways to enhance their ability to conduct comprehensive ocean observation. To organize an experiment in the near-term, a decision was made to use commercial-off-the-shelf technology that was mature and which met the exercise objectives. Based on these criteria, one US corporation (Maritime Tactical Systems, Inc.) was invited to demonstrate the use of its unmanned surface vehicle (MANTAS) to conduct a comprehensive an environmental monitoring evaluation. This month-long endeavor was conducted under the auspices of the Naval Meteorology and Oceanography Command.

Under the command's stewardship, an advanced naval training exercise was conducted in the Gulf of Mexico, south of Gulfport, Mississippi. Okon put the importance of the exercise this way: "This is the Navy's premier showcase for emerging technology, especially emerging unmanned technology. It enables us to build better partnerships with industry and academia and to achieve our strategic goal to innovate."[8]

Naval Meteorology and Oceanography Command scientists outfitted a commercial Maritime Tactical Systems unmanned surface vehicle with an Environmental Monitoring System developed by the command. These systems and sensors were designed to be carried by this vehicle to provide a one-platform solution to important environmental sensing that was, in the past, conducted by multiple platforms.

The package included nine sensors (not all were used during the exercise). These included: Teledyne Benthos ATM603 Underwater Modem, FLIR M232 Camera, Teledyne Citadel CTD-NH Conductivity Temperature Depth Monitor, Teledyne DVL with ADCP Doppler Velocity Log, Norbit iWBMSh-STX Echosounder, Turner C3 Fluorometer, Quanergy M8-1 Plus LIDAR, Airmar WX220 MET Meteorological Sensor, and SeaView SVS-603 Wave Height Sensor. This sensor data was communicated in real time to the Meteorology and Oceanography Command control station.

A second unmanned surface vehicle, this one equipped with a different suite of ocean monitoring systems and sensors, was employed to conduct a second round of testing. The sensors employed included an iWBMSh-STX and Klein UUV 3500 side-scan sonar. As testing continued with both vehicles, scientists and engineers provided vital feedback and suggested several enhancements to these vessels including improved solar amp meter gauges, collision avoidance improvements, tracer self-configuration, and a system status indicator, among others. This iterative process between developers, operators, and engineers was inspired, in part, by past ONR work—in conjunction with the Navy laboratory community—in the area of user-centered design.

While the full details of the ocean observations collected are beyond the scope of this article, they included: wave height, wave frequency, current speed and direction, wind speed and direction, air temperature, barometric pressure, fresh and salt water concentration, and bottom

A close up of the 12-foot MANTAS vehicle shows its various instruments and solar panels. Photo by Maritime Tactical Systems, Inc bathymetry/contour. All of these measurements are essential components that feed environmental models vital to naval operations and also contribute to important data-driven decisions regarding climate change. In addition, it was demonstrated that the unmanned surface vehicle was able to communicate with an unmanned underwater vehicle for further mapping of the seafloor. The sensor package, as deployed, was also able to record the water quality for red tides.

The ability to conduct surveys in higher sea states had thwarted other unmanned surface vehicles in the past, but was one of the highlights of this month-long event. The catamaran-hulled MANTAS was able to operate in sea state five conditions. In addition, the vehicle is configured with line replaceable unit electrical junction boxes to protect sensor components in heavy weather.

A New Model for Persistent Ocean Observation

Given the ongoing importance of collecting the right environmental information at the right time at the right place to support the fleet and forces, as well as help make data-driven decisions to address the national security implications of climate change, finding a cost-effective means to collect this oceanic information autonomously while having humans on the loop (as opposed to in the loop) is crucial.

The use of commercial unmanned surface vehicles successfully employed during this demonstration can be readily scaled up in platform size and thus provide for added oceanographic sensors. This will allow for a further extension of capability within specific oceans, seas, bays, rivers, and other waterways, and can also lead the way for enhanced data collection, transmission, and evaluation of water conditions and the ocean environment.

Navy officials have encouraged Maritime Tactical Systems to scale up the 12-foot MANTAS used for this exercise effort and produce larger vehicles to conduct more comprehensive ocean observation. In 2020, a larger 38-foot unmanned surface vehicle, now referred to as the DEVIL RAY T38 was deployed during Navy exercise Trident Warrior. These larger vessels (including 24-foot and 50-foot DEVIL RAYs on the drawing board) could be ideal to conduct extended and more detailed ocean observation with their added ability to carry considerably more sensors and remain at sea for longer periods.

As one example of what this increased size provides with regard to ocean observation, a 24-foot or 38-foot DEVIL RAY, using an ocean bottom surveying speed up to 15 knots, can remain under way for up to seven days until it needs refueling, after which it can again resume its survey mission. Multiple unmanned surface craft can be used to perform concurrent, independent scans within the same area, thereby greatly increasing the amount of total area that can be surveyed.

Leveraging these larger vehicles to accomplish these priorities will go a long way toward making data-driven decisions to provide valuable environmental information to the Navy and Marine Corps as well as help government agencies make better data-driven decisions to address climate change.

The Navy, NOAA, and many other stakeholders recognize the critical need for understanding the ocean environment. Indeed, one trade publication, *Ocean News and Technology*, dedicated a major portion of its December 2020 issue to articles discussing ocean observation. Therefore, there will likely be an increased demand for unmanned systems prototyping and experimentation to support comprehensive ocean observation. The vast array of technologies emerging in today's unmanned maritime systems provides a tremendous opportunity to move forward with an effective and affordable ocean observation taxonomy.

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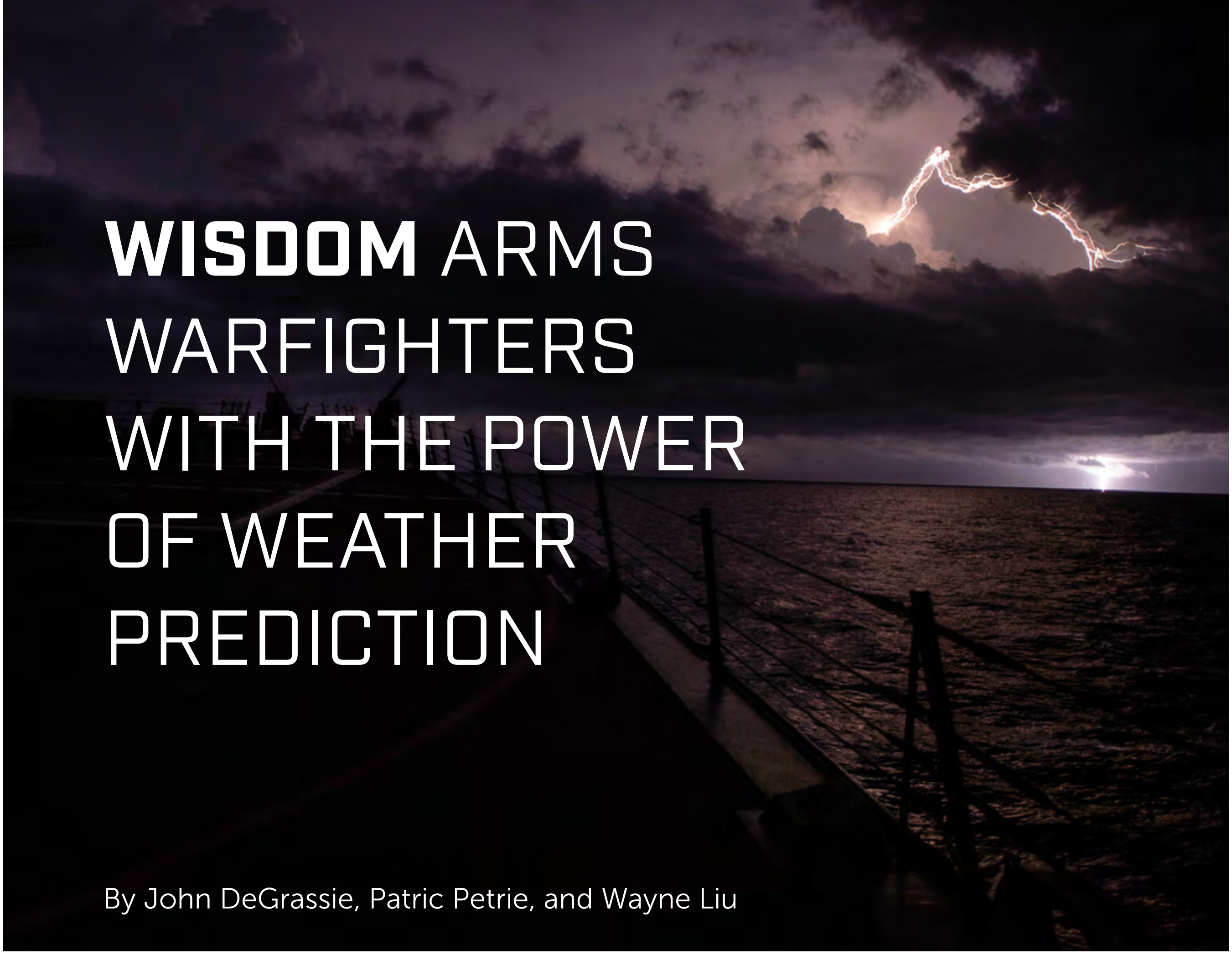


Photo by PO3 Jack Aistrup

WISDOM ARMS WARFIGHTERS WITH THE POWER OF WEATHER PREDICTION

By John DeGrassie, Patric Petrie, and Wayne Liu

WEATHER-INFORMED SPECTRUM DOMINANCE—MADE POSSIBLE BY A SERIES OF PROGRAMS AT THE NAVAL INFORMATION WARFARE CENTER PACIFIC—ENVISIONS AN ENVIRONMENT WHERE KNOWLEDGE OF CURRENT AND FUTURE WEATHER TRANSLATES INTO BATTLEFIELD SUCCESS.

Information has always been a deciding factor in battle. Those with the most accurate and up-to-date information, and who can use it in real time, possess an extraordinary advantage over an enemy. The mission of Naval Information Warfare Center (NIWC) Pacific is to make sure warfighters can access all relevant information to make the best decisions to achieve mission success.

The amount of information in the battlespace is growing at an ever-increasing rate, and warfighters need reliable systems that process and deliver actionable data. Information warfare is not just another warfighting domain; it is the principal domain, supporting all others.

Environmental effects, local weather conditions, and meteorological and oceanographic (METOC) data are significant components in information warfare. The modern battlespace is composed of diverse geographic and spectral environments, where local conditions change continually. Knowledge of how local environmental conditions are affecting sensors and lasers can provide those critical seconds for offensive or defensive actions or optimizing force dispositions.

To meet the demands of this new information warfare front, the Atmospheric Propagation Branch at NIWC Pacific is building capabilities so warfighters can achieve full weather-informed spectrum dominance (WISDOM). The essence of this concept is that warfighters can maximize system performance, and minimize vulnerability, by putting to use accurate and up-to-date information on how the environment affects their systems as well as those of their enemy.

What is WISDOM?

WISDOM is a system architecture, an organizational framework, and a vision. It is composed of hardware and software systems that sense, model, and predict how electromagnetic signals propagate in the battlespace.

The WISDOM framework identifies three components necessary to increase the accuracy and timeliness of electromagnetic system performance informed by the real-time local sensing and dynamically changing battlespace conditions. First, data-driven and physics-based models transform weather data into system performance data (e.g., radar range, radio throughput, and probability of detection). Second, inversion algorithms map sensor data into near-real-time estimates of atmospheric conditions. These are embedded systems that place no additional training requirements on operators. Finally, data fusion and machine learning methods use the accurate local weather assessments from step two to update the inputs to the models used in step one for the entire region of interest. Accounting for the nuance of the real-time weather improves the accuracy and timeliness of predicted electromagnetic system performance.

The WISDOM system architecture outlines how components of the framework fit together. It shows the various components of platforms and data support infrastructure and how each interacts with the three main components. This provides insight into how WISDOM delivers more accurate and up-to-date system performance assessments to a mission.

Walking through an example in radio frequency atmospheric propagation will illustrate further the architecture's three components.

As signals propagate in the atmosphere the paths they follow can bend and are not necessarily straight lines; this is analogous to why a pencil or straw appears bent when placed into a glass of water. Refractivity is the atmospheric parameter that characterizes and determines how much signals will bend in the atmosphere. This bending can create interesting propagation phenomena, such as increased propagation distances, the shadows zones where energy does not propagate.

Refractivity depends on local weather conditions, such as temperature and water vapor. The Navy's Fleet Numerical Meteorological and Oceanographic Center produces forecasts of these variables, much like weather forecasts seen on local news. The forecast of refractivity provides warfighters with the best estimate of the propagation conditions in the battlespace, predicting how it changes in space and time. With this information, the first step to full radio frequency WISDOM can be taken and signal system performance data can be generated from the weather inputs using the Atmospheric Propagation Branch's predictive models.

The temporal and spatial resolution of forecasts, however, may not capture all relevant conditions of the in-situ battlespace environment, just as a local news forecast does not predict the precise state of the weather around one's home. Therefore, bringing knowledge of the actual refraction conditions in situ is necessary to capture the full nuance of the battlespace spectrum. NIWC Pacific's purpose-built environmental sensors and inversion methods that monitor radio frequency system performance metrics in the battlespace can determine these in-situ conditions. This is the second step toward full WISDOM, where the environmental conditions that correspond to the observed signal performance are sensed and algorithmically determined. This step results in a collection of refractivity data points corresponding to the actual in-situ conditions, at that very moment.

These data points, while local and real-time, are not full descriptions of the entire battlespace; they are accurate measurements of the environment at specific locations. To bring this knowledge to the full battlespace, the Atmospheric Propagation Branch takes the final step to full WISDOM using data fusion and machine learning to update the full spectral picture. Warfighters then have a more accurate and up-to-date prediction of the radio frequency system performance, and they have more confidence in how this will change in time and space, as the mission evolves. With each complete cycle of the three WISDOM components, warfighters' battlespace spectral dominance deepens and the nuances of how and where electromagnetic signals propagate more fully buttress the operational information landscape.

Melissa Sanders, a mechanical engineer at Naval Information Warfare Center Indo-Pacific Department, tests a DJI S900 hexcopter with a Tri-Sonica Mini-Weather Sensor at Bellows Air Force Station in Hawaii.Photo by Dexter Barit

The Future of WISDOM

The Atmospheric Propagation Branch is working with the Naval Research Enterprise and Department of Defense to advance WISDOM—improving underlying models and connecting the required components—by driving toward increasingly accurate and real-time EM system performance assessments and predictions. Recognizing that the amount of information in the battlespace is growing at an ever-increasing rate and that warfighters need reliable systems that process and deliver actionable data, the branch is working to make WISDOM as transparent to warfighters as possible. In the future, the systems themselves also will be armed with WISDOM and will automatically adapt to the environment.

NIWC Pacific is building WISDOM for the full electromagnetic spectrum, across the high-frequency, radio-frequency, and electro-optical domains. Each portion of the spectrum has unique challenges that must be met and overcome so warfighters can operate with confidence in knowing precisely how their systems will work in every weather condition. The scientists and engineers at the Atmospheric Propagation Branch work to ensure this confidence is well placed through a range of efforts:

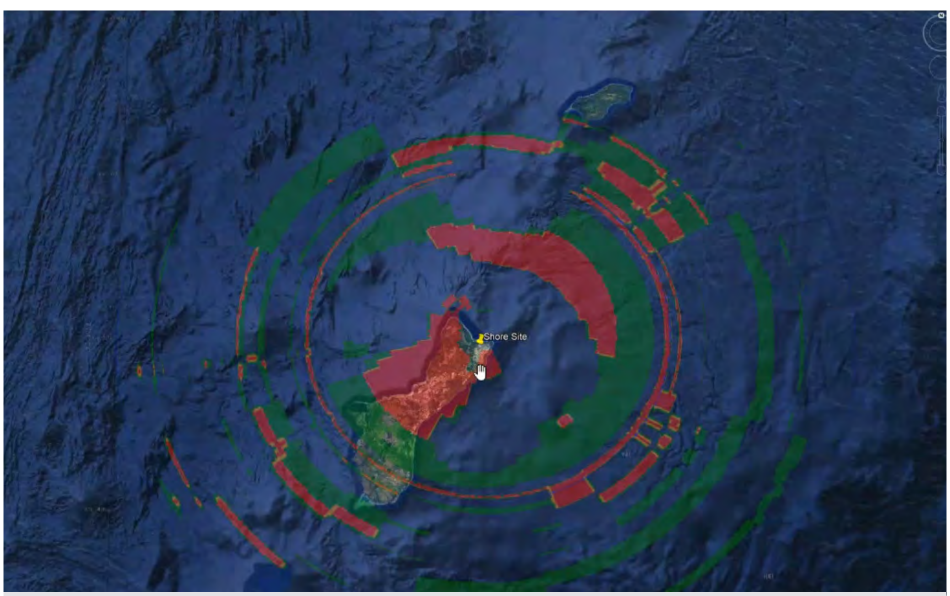
- **Digital Adaptive Optics:** An optocomputational solution to imaging challenges in turbulent atmospheric conditions. Images that are corrected for atmospheric distortion by this system will provide an opportunity for in-situ sensing for the second component of electro-optical/infrared WISDOM.
- **TrueView:** A hyperspectral, physically accurate electro-optical/infrared image and signature simulation engine provides accurate predictions of imagining sensors for any atmospheric conditions. By transforming weather information into electro-optical/infrared system performance, TrueView is the first component of optical WISDOM. TrueView is planned to transition soon, providing unparalleled weather-informed imaging metrics.
- **Path Characterization System:** A WISDOM component for forward predictions of optimal geometries, atmospheric imaging, and high-energy laser performance given in-situ atmospheric measurements and weather forecasts.
- **IonosphericRayTrace:** Predictions of high-frequency propagation driven by the current and predicted conditions of the ionsophere.
- **Radio Frequency Propagation Prediction and Assessment Suite:** Accurate and timely predictions of radio frequency propagation metrics using in-situ and weather prediction atmospheric data that are the critical first component in WISDOM. This suite is currently part of the system used in daily naval operations.
- **Refractivity from Clutter for SPS-48/Hazardous Weather Detection and Display Capability:** This is likely to be the Navy's first operational inverse problem solver. It takes the radar clutter extracted by the Hazardous Weather Detection and Display Capability and compares that to thousands of clutter "replicas." It then outputs the atmospheric refractivity profiles most likely associated with the observed clutter; this is a complete second WISDOM component.
- **Refractivity Data Fusion:** The first-generation research and development version of this system was focused on fusing local refractivity observations with background fields from numerical weather prediction for the third component of WISDOM. NIWC Pacific plans to expand its functionality to include ingesting meteorological observations from sensor packages on unmanned aerial vehicles.

Other Weather-Related Capabilities

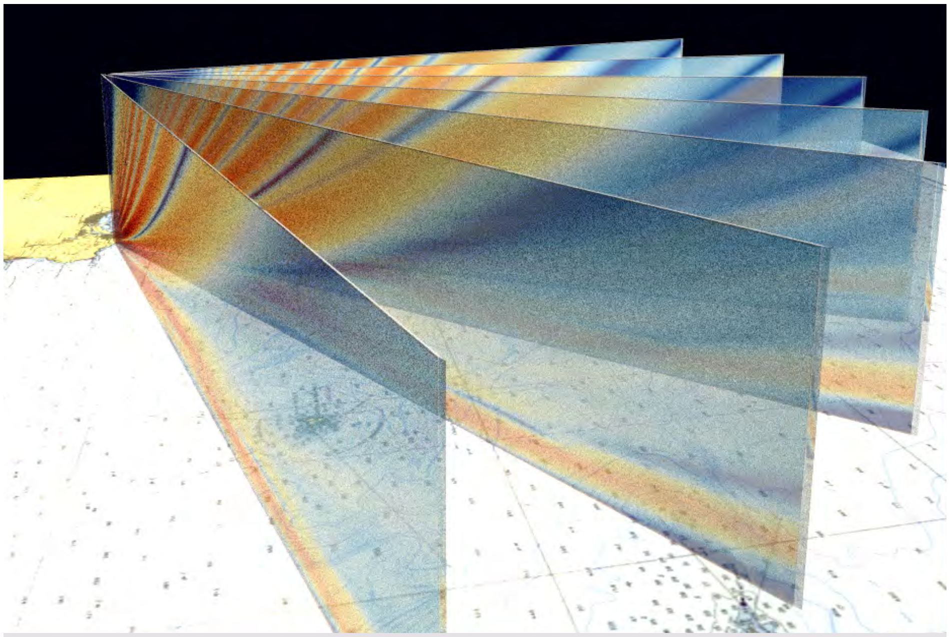
In support of WISDOM, an internally funded Naval Innovative Science and Engineering research project known as In-Situ Refractive Evaporative Duct Measurements seeks to demonstrate how self-charging, unattended quadcopters can autonomously carry lightweight METOC sensors into the atmosphere to profile critical temperature, humidity, and wind conditions that can impact communications and airborne/sea-based operations.

This novel capability will enable on-demand, highly distributed and in-situ weather measurements by tasking unmanned aerial systems that can profile atmospheric conditions and then autonomously return home to a network of wireless charging pads for battery replenishment. As a sustainable remote network, this function will provide a capability for on-demand, in-situ METOC, to enable WISDOM in command, control, communications, intelligence, surveillance, and reconnaissance operations.

This project is a cross-departmental effort at NIWC Pacific. The Atmospheric Propagation Branch is providing support for the atmospheric sensors and modelling and our Indo-Pacific department is providing the unmanned aerial system and sensor integration and testing in Hawaii's operationally relevant environment.



This visualization using Google Earth shows the modeled probability of detection for a generic surface radar site using numerical weather prediction. Graphic by Rick Navarro



This screen shot uses three-dimensional software to display radio frequency propagation metrics to explore different ways of human-computer interaction for WISDOM data displays. Graphic by Edward Bertot and Neil Gordon

technological improvements and the electromagnetic spectrum getting ever more crowded, it is imperative that the satellite capability remains relevant for the METOC community.

To support the Marine Corps, as well as other authorized operations worldwide, forecasters deploy a component of the Meteorological Mobile Facility (Replacement) Next Generation, known as the Meteorological Satellite Subsystem, to capture, process, display, and analyze weather's effects on the battlespace.

As part of the changes occurring with the management of the electromagnetic spectrum, the team's experts are working with partners and industry to design and integrate a system that consists of a three-band spectrum capability: S-band, L-band, and X-band. This capability allows the subsystem to continue to be operational and align with the frequency spectrum transition to commercial use by Federal Communications Commission.

METOC Capability-Based In-Service Engineering Agent

This group's diversified team consists of engineers, computer scientists, information technology and cybersecurity specialists, technicians, and logisticians.

They provide technical sustainment support, sustainment engineering, logistics support, modernization support, and software activity support both to the fleet and force worldwide. Projects include the Hazardous Weather Detection and Display Capability, Meteorological Mobile Facility (Replacement) Next Generation, Naval Integrated Tactical Environmental System Variant IV, and Naval Integrated Tactical Environmental System Next Generation.

To any meteorological forecaster, the ability to "look" down and see the weather from space, either over or in route to the area of interest, is groundbreaking. These eyes in the sky are geostationary and polar-orbiting meteorological spacecraft that belong to the National Oceanographic and Atmospheric Administration and the US Air Force. Meteorological imagery in several forms is captured by these orbiting satellites, processed, and transmitted to ground stations back on Earth.

The METOC defense community receives and analyzes satellite imagery to monitor meteorology and oceanography conditions/elements, and is used to analyze the weather's impact on military operations. Forecasts and other analyzed products that enhance battlespace awareness are provided to decision makers in areas with ongoing Department of Defense operations. With constant

The METOC Capability-Based In-Service Engineering Agent received the delivery of the first lab-system in November 2020. They are still working to support the delivery of the test article in 2021, which will include the X-band Nonrecurrent Engineering System.

Once the government verifies that the replacement system meets the stringent system requirements, industry will produce and deliver two systems a month until full system fielding, starting in spring 2022.

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Photo by US Naval Research Laboratory

INTERVIEW

"WE EXECUTE SCIENCE and TECHNOLOGY DEVELOPMENT and TRANSITION CAPABILITY to the FLEET"

By Capt. Edward Lundquist, USN (Ret.)

CAPT. LUNDQUIST SPOKE WITH DR. BRIAN HOUSTON, SUPERINTENDENT OF THE ACOUSTICS DIVISION AT THE US NAVAL RESEARCH LABORATORY, ABOUT ANTISUBMARINE WARFARE, UNMANNED UNDERWATER VEHICLES (SUCH AS THE BLACK PEARL SEEN HERE) AND THE LABORATORY'S LATEST RESEARCH IN ACOUSTICS.

LUNDQUIST: You are the director of the acoustics division here at the Naval Research Laboratory (NRL) in Washington, DC, which comes under the Office of Naval Research (ONR). What's the purpose of NRL, and what is the relationship between ONR and NRL?

HOUSTON: As the Navy's corporate laboratory, the purpose of the Naval Research Lab is to be cognizant of—and have world-class expertise in—the very basic sciences that are fundamental to all the technologies that we have in our society, and to create new technology through continued investment in science at the very basic level. NRL comes under the Chief of Naval Research as head of the Office of Naval Research (ONR). ONR directs much of the work of the Naval Research Enterprise (NRE), of which we are a part, along with Navy warfare centers, academic institutions and federally funded research and development centers. We have a very close relationship with ONR, both as our reporting command and as a research partner. We are a working laboratory at NRL, and we execute science and technology development and transition it to the fleet. Our work is basic and exploratory, all the way up to applied research and transitions. Unlike many of the organizations in the NRE, we also do very basic science work—so called 6.1 level work—where you have people on the lab, for example, that are developing new mathematical theories, and making new materials using surface science techniques, or developing new optics and lasers at the very fundamental level. Like much of NRL, in the acoustics division we intertwine that very basic science with exploratory research (6.2 research) where it's more applied, taking what we've learned from the basic science and identify what can evolve into technology that might eventually benefit our warfighters.

LUNDQUIST: It's a bottom-up approach where you intertwine basic science with new technology.

HOUSTON: Yes. We also have to be cognizant of the work being conducted by our colleagues in other organizations, such as Navy warfare centers, university labs or foreign research facilities, and we also carry out scientific research here at a very basic level. If you look back at the invention of the transistor, for example, and what it took in order for that to become an practical ubiquitous device that we use today, there was a lot of very fundamental theoretical and experimental work in solid-state physics that led to the development of the first transistor. NRL is one of the organizations in the NRE, but we differ from almost everyone else because we try to take new science and develop new technology from it. In contrast, many others tend to engage in only engineering refinement. And when you see some NRL research that's resulted in a breakthrough technology or capability, you're just seeing the tip of the iceberg. That's because there is so much basic science behind it. Our technology development teams that are bringing new capabilities and systems to our ships, aircraft and submarines have scientists who understand the very basic physics integrated with those technology teams.

LUNDQUIST: How long have you been here at the lab?

HOUSTON: I've been here 35 years. I came to NRL originally as a student and it just became a home very quickly because of the people and facilities that are here and the really great problems we have to solve.

LUNDQUIST: When you talk about basic and applied science together, what is the problem you and your team are trying to solve?

HOUSTON: The Navy is interested in being able to successfully carry out undersea warfare, which is really a broad spectrum of problems. Antisubmarine warfare (ASW), for example, where we need to be able to detect, track, and engage threat submarines, is just one aspect. But today it's not just submarines. Today we have autonomous underwater vehicles and some of these vehicles are large, with a lot of energy, and they will be weaponized by adversaries one day. As we look into the future, unmanned vehicles will be enabled with very sophisticated artificial intelligence, carrying out the mission that are today performed primarily by manned submarines. So undersea warfare is ASW, but it's also anti-unmanned underwater vehicle (UUV) warfare, or what some people like to call "counter-UUV warfare." How do we deal with those unmanned systems that are coming in the very near future—they're going to be very capable, with a lot of energy, and will be smaller and harder to detect and localize. You can't engage such a threat unless you can detect, localize and track it. There are a lot of different problems associated with that—it's not just a sensing problem, it's also an enormous environmental acoustics problem. Understanding the acoustic environment, and how sound propagates underwater, is a big part of that problem, and it's one of those things that we're engaged in at the basic, exploratory, and applied level. If I stand on a mountain, and look out at another mountain, most of that light propagates in a straight line. It's different in acoustics. Sound doesn't propagate in straight paths. It bends vertically, depending on the sound-speed profile. Sound can refract horizontally, too. Sound doesn't go in a straight line, and just the interaction between sound and the water volume itself makes the whole problem much more challenging and the environment is a huge piece of the overall challenge. It's also one of those areas that NRL excels at.

WHEN YOU SEE SOME NRL RESEARCH THAT'S RESULTED IN A BREAKTHROUGH TECHNOLOGY OR CAPABILITY, YOU'RE JUST SEEING THE TIP OF THE ICEBERG.

LUNDQUIST: Does your work involve unmanned underwater vehicles?

HOUSTON: We use unmanned systems in our research, a lot. They're not just platforms to put sensors on, or use as scientific measurement tools. We're also trying to figure out how to use them in undersea warfare. We're engaging in the development of the artificial intelligence that's needed to make those platforms work for the Navy. We're figuring out how to best use them in terms of sensor platforms, in an applied way, the way the Navy might apply them in terms of an offensive capability. There's a lot going on here.

LUNDQUIST: Because this is the acoustics division, I assume your work is using different kinds of sonar.

HOUSTON: The acoustics piece of undersea warfare represents a lot of what we do—and it's a very challenging area. That includes finding things in the water, like submarines, and things on the seabed, like mines. The seabed is also a place for sensors, communication nodes, and offensive systems, for example, so we have to look at how we will deal with these in the future. It's always been an issue for the Navy, but today seabed warfare is much more acute and focused. Antisubmarine warfare continues to be a huge challenge, and the threats are becoming more sophisticated. It's not just something in the water that you're looking for, but something that's moving in a difficult environment that is stealthier than its predecessors and doesn't want to be found. A major area encompassed by undersea warfare is mine warfare, and not just offensive mines, but how to detect and localize adversary mines and how to deal with them. A mine is a very inexpensive weapon, and it's relatively easy to make a mine effective. It costs very little compared to the targets it goes after, like a billion-dollar warship, for example. They're very difficult to detect and classify. We worry about mines today as much as we ever did. With regard to detection, there is a lot of stuff in the water column and even more stuff on the bottom. Mines are typically used in close proximity to the bottom, so you have to sort out the mines and detect and classify them in the context of all of this clutter and the topology of the bottom itself. It's another tough undersea warfare problem.

LUNDQUIST: Do you find that you focus more on ASW? The seabed? Unmanned? Or mine warfare? Or all of the above?

HOUSTON: It's all of the above. I'm the acoustics division superintendent and all of those challenges you just mentioned have been areas that I've worked on during my 35-year career here at NRL that continues today.

LUNDQUIST: Today do you find yourself working on platforms, sensors, processing, or on the systematic employment of all of that together?

HOUSTON: I think the latter is probably the most descriptive.

LUNDQUIST: You have led the development of low-frequency broadband (LFBB). What does that mean?

HOUSTON: LFBB is our term for a technology area that we developed here at NRL that exploits the structural acoustics involved with underwater sonar. When you transmit sound, the acoustic return is very different depending on the physical object that is reflecting that acoustic energy. It might be a naturally occurring thing like a rock on the bottom, or something that's man-made, like a mine. In the water column, it might be a submarine versus a whale. What's in the acoustic return is very different for each of those targets. Sonar has traditionally helped us know where something is, how far a way it is, and sometime provides an image. But in addition to bearing and range, we can now determine what it is. That return has specific physics in it that we can exploit, and we can know something about the physical object and based on how it responds.

LUNDQUIST: Does that require new kinds of sensors, or just new ways of analyzing the sensor data?

HOUSTON: It's really both. We developed both a sensor approach as well as how to analyze the data to learn those things. That whole technology area is what we call "low-frequency broadband." We have our Reliant and Black Pearl vehicles to help us with the development of LFBB in applications for mine countermeasures as well as ASW and counter-UUV applications. These are NRL research UUVs that are built on a commercial vehicle construct—the propulsor and the power system are based on a commercially available vehicle, with our sensor being the special piece of technology on those vehicles that makes them unique. These are research vehicles we used to develop and ultimately transition the technology. They're exclusively used for that research. Reliant is a little bit older vehicle with what I would call a first-generation sonar. And then Black Pearl is an updated vehicle with a sort of a second-generation sonar that carries with it the ability to do LFBB at much longer ranges.

LUNDQUIST: Are these 12-inch or 21-inch vehicles?

HOUSTON: They are 21-inch-diameter vehicles from General Dynamics Bluefin Robotics.

LUNDQUIST: How many of them does NRL have?

HOUSTON: These are research vehicles, and so we don't need an army of them to carry out our research. We have three of them.

LUNDQUIST: When you develop an experiment plan to take a sensor out and see how it performs against known targets, do you use an existing range?

HOUSTON: We design and execute our own experiments and typically we set up our own ranges. We sometimes participate in fleet exercises where the environment is typically less known, but our requirement is to generate defendable, quantitative results. With respect to mine hunting, some of the traditional and well-used ranges have been used so much by the Navy for testing and training that there is a lot of stuff left on the bottom that can make it difficult to develop a ground truth. Old targets and other objects that are not part of the ground truth can generate false alarms and interfere with our testing. We have to be able to go in, search an area, and tell the Navy how well we did against some valid ground truth. It's much more straightforward and a better experiment to go into an area that's relatively pristine without old uncharted debris, then plant a new field, run the experiment and get performance numbers. That usually produces much more defendable performance numbers than to go into an area that's been used heavily for 50 years.

MNCS Abraham Garcia (left) and AG1 Joshua Gaskill, members of the Knifefish unmanned undersea vehicle test team, man tending lines during crane operations as part of an operational test. Knifefish is a medium-class mine countermeasures vehicle designed for deployment off littoral combat ships. Photo by MC1 Brian M. Brooks

LUNDQUIST: A lot of what vehicles do in mine warfare is change detection—knowing what's on the bottom, and coming back later to see if anything has changed.

HOUSTON: You can do change detection with almost any sonar system, including our systems, but we do not rely on change detection. Our system operates at a very high-performance level to go into an area and you can rely on the results from just a single pass. That's the objective.

LUNDQUIST: Are your Black Pearl and Reliant vehicles pretty much similar to other UUVs?

HOUSTON: The major difference is the sonar itself. One of the reasons why we like the General Dynamics Bluefin Robotics 21-inch vehicle—both Reliant and Black Pearl are Bluefin vehicles, in that they are what I call "open ocean capable." In other words, they have a lot of energy on them, they have fairly high-end navigation systems, plus we have other things on them that make them very useable and capable in the open ocean. We also can go into shallow water areas and even very shallow water areas. So, we like that aspect of it. We want to have some "legs" on the vehicle and navigate accurately. The sensors themselves aren't consistent with a small vehicle, particularly because the low frequencies require larger sources and sensor apertures. An example would be ASW applications where very small UUVs don't have enough energy to really go anywhere and the sensor platforms that you can put on them are also small, and thus low performance. We find that the 21-inch format is very, very good for the kinds of things that we want to do in our research and applications.

LUNDQUIST: Are you collecting data and bringing it back? Or are you somehow transmitting data back so you're getting information in real time?

HOUSTON: We can do that, but typically what we have done is to bring data back and do the analysis offboard. Today we are now doing a lot of onboard processing, so we can take the data and process it on board the vehicle to enable autonomy decision making. The autonomy is enabled by the sensors, so it has access to the real time processing of the sensor data, and it makes decisions based on that. One of the goals of developing future systems for the Navy is to have sensor-aided autonomy. You can think of it as being analogous to leaving an office building downtown and walking out the front door with your eyes closed, trying to navigate the streets of a busy city just by listening. You're processing sound, whether it's an active sonar or passive sonar, you're processing sound and at some point, you have to make a decision about what the different sounds are and what to do about them. With this kind of information, the UUV might pursue, loiter, or go to the bottom and hide. You use the sensors and the autonomy together. That's the basic construct.

OUR SYSTEM OPERATES AT A VERY HIGH-PERFORMANCE LEVEL TO GO INTO AN AREA AND YOU CAN RELY ON THE RESULTS FROM JUST A SINGLE PASS. THAT'S THE OBJECTIVE.

LUNDQUIST: Do your vehicles collaborate with each other?

HOUSTON: We're interested in increasing our coverage area and coverage rate. So, we would like to be able to search an area, for example, with a team of vehicles equipped with sensors, and using low-bandwidth communications, or in some cases no communications, and operate together to clear an area. Also, one way to look at collaboration, for example, is if we have a magnetometer on one vehicle and an acoustic sensor on another. Here, we're looking for the orthogonality [statistical independence] of those two different sensors to improve classification decisions.

A lot of what goes on in undersea warfare—whether it's ASW or mine countermeasures or whatever—typically requires high coverage rates. And obviously, the more vehicles you use allows you to increase your coverage rate. One of the artificial intelligence questions that we're dealing with is how to do that efficiently. And one of the critical issues is communication: do I have high bandwidth communications between vehicles so that they can talk to each other? These typically have to be simple messages. Underwater acoustic communications are typically short range in the way they can be implemented practically. For more complex high-bandwidth communications, the vehicles have to be very close to one another, or come to the surface and use a satellite or radio. We're working on algorithms so that a group of agents—vehicles—can work cooperatively, and do their job without talking to each other very much, if at all. In an undersea warfare situation where the systems are spread apart, they have long range capability only in terms of sensing, but communications between them often means they have to be closer together. That's why building the artificial intelligence to make cooperative behaviors work with very limited communications is one of those things that we're working on.

LUNDQUIST: Is LFBB a side scan sonar or a synthetic aperture sonar?

HOUSTON: Typically, side scan is older technology, where synthetic aperture is the more modern implementation of the side scan sonar yielding higher spatial resolutions. LFBB is an active sonar that employs synthetic aperture processing and the processing also uses artificial intelligence to detect and classify.

LUNDQUIST: How has your LFBB research found its way into a program of record, such as the Knifefish surface mine countermeasures UUV that is part of the mine countermeasures mission package for the littoral combat ship and other vessels of opportunity?

HOUSTON: The Knifefish system is focused on mine hunting, and, as it's currently configured, is largely based on the work that we've done on LFBB hardware and the artificial intelligence-based processing of the data.

LUNDQUIST: You are the director of the Acoustics Division here at NRL. What does that entail?

HOUSTON: The acoustics division has three main branches. Two of those branches (the Physical Acoustics Branch and the Acoustics Signal Processing and Systems Branch) are located here in Washington at the NRL main campus. The third (the Acoustic Simulation and Tactics

The NRL Acoustic Division's Black Pearl autonomous underwater vehicle being recovered in the approaches Boston Harbor carrying advanced structural acoustics sonar payloads. Black Pearl is an updated vehicle with a second-generation sonar carrying with it the ability to do low-frequency broadband (LFBB) at much longer ranges. LFBB is an active sonar that employs synthetic aperture processing and the processing also uses artificial intelligence to detect and classify objects of interest. Photo by US Naval Research Laboratory

Branch) is located on the NRL campus of the Stennis Space Center in Mississippi, and is primarily focused on environmental acoustics for fleet ASW problems. In Acoustics Signal Processing is where we do a lot of fundamental work that is, in part, focused on aiding ASW processing systems for destroyers and submarines as well as Arctic acoustics and acoustic communications. The Physical Acoustics Branch has a broad program that spans phonon transport physics in materials through the structural acoustics of submarines, UUVs, and mines. It is also where we have our Laboratory for Structural Acoustics.

LUNDQUIST: When you talk about "structural acoustics," what does that mean?

HOUSTON: Structural acoustics focuses on the interaction of the sound with structures in a fluid—in this case were talking about heavy fluids like water. If I ping on an object underwater the sound will propagate across the water volume and interact with the structure. The acoustic energy will cause the casing of a mine, or the hull of a submarine, to vibrate at the angstrom level. So, the interaction of sound with a structure, and then the re-radiation of sound is the realm of structural acoustics. Some years ago, we put together the Laboratory for Structural Acoustics to focus on precision measurements in structural acoustics. The primary element is a large, in-ground, vibration-isolated water tank, equipped with anechoic coatings and robotically controlled acoustic sources and receivers. Here, we do a lot of experimentation in structural acoustics employing compact range and nearfield acoustic holography techniques.

LUNDQUIST: Is it a one-of-a-kind facility?

HOUSTON: Yes.

LUNDQUIST: I would imagine that other people who are interested in this kind of experimentation might benefit from a facility like this.

HOUSTON: In addition to our own research, we have research partners that come here to NRL and work with us.

LUNDQUIST: What is the Navy's return on the investment for the work you are doing here?

HOUSTON: That's a broad question, but I'm going to try to be fairly focused in my response. As I said earlier, NRL is fairly unique in the way it responds to Navy needs. The applications and technologies that are generated here at NRL are intimately tied to basic science. We maintain a close contact with the science and the applications. In the case of LFBB and ultimately the transition to the Knifefish program, a lot of that work started as very basic physical and structural acoustics science. The work carried out at the basic science level at the NRL acoustics division over a number of years, ultimately turned into sensor systems, processing methodologies, and artificial intelligence-based classifiers that exploited those signatures and gave us the ability to tell the difference between structures with a fairly high level of accuracy. Here, the return on investment, just based on the cost of the deployed system compared to the research investment, is greater than 100 to 1. If you move away from what we're doing in the acoustics division and look at some of the other divisions at NRL, the applications that end up on a gray ship are explicitly tied to knowledge of the basic science. So, we're not just approaching these problems based on general established principles. Many of our team members here at NRL are accomplished, world-class scientists, but we're also capable engineers and technologists so that we can turn new science into something that the Navy needs. If we hadn't approached our research this way, starting at the very basic level, we never would have gotten to LFBB. Early on, there were people involved with mine countermeasures that said LFBB can't work because those views were largely based on old science. We faced a lot of pushback. But after the sort of intellectual discussion and debate that goes on over time, we ended up being able to convince many naysayers that there was a lot of power in this new technique. And ultimately after we demonstrated at-sea performance, we were successful in getting the technology sold. But my point is that the ideas came from basic research—the science that started it all.

LUNDQUIST: That's the message—investing in basic research can lead to transitioned technology in the hands of warfighters.

HOUSTON: We typically have a vertically integrated workforce. We have the basic researchers who are typically world-class scientists. There's a huge difference between an engineer and a scientist. But we have basic scientists that are really in touch with the fundamental physics and so on and so forth, but they're integrated with people who are more applied. Our scientists, engineers, and the people who know how to bend metal and make it function, are all working together in an integrated fashion. It actually accelerates the transition of scientific discoveries to applications. If you don't have that connectivity, you just can't make the arguments that will bring a new piece of science to an application that the fleet needs.

LUNDQUIST: Is Knifefish kind of an example of that? Does Knifefish resemble what you were experimenting with on Reliant or Black Pearl before there was a Knifefish? Can you see the results of your efforts becoming a reality in Knifefish?

HOUSTON: Yes. That's the interesting thing about the whole process. We strive to meet a requirement. As the system achieves success, the bar is raised and requirements get ratcheted up. For the Navy, mine hunting is a very challenging problem. It's a challenge that gets a little bit more difficult as time goes on. The challenge isn't the same in 5th Fleet, for example, compared to 6th Fleet or 7th Fleet. The threat changes as a function of geography, and we have to respond to new requirements as time goes on. Being able to adapt the technology to handle a new set of problems is one of the things we're involved in right now.

MANY OF OUR TEAM MEMBERS HERE AT NRL ARE ACCOMPLISHED, WORLD-CLASS SCIENTISTS, BUT WE'RE ALSO CAPABLE ENGINEERS AND TECHNOLOGISTS.

LUNDQUIST: Have you been involved in some of the fleet experimentation, such as deploying Knifefish from vessels of opportunity, such as a British auxiliary ship and the expeditionary sea base?

HOUSTON: Yes. And we have prototypes that are very close to the actual system that can be used for testing, and we have been able to directly support some of the testing and evaluation.

LUNDQUIST: I presume that the testing or experimentation is done to closely approximate how the operators would use it, and it must be gratifying to see it finally doing what all that basic research suggested would work back in the beginning.

HOUSTON: It certainly is very gratifying. And the other piece of all of that, of course, is responding to what the fleet thinks that it needs. When you get it in the hands of sailors, the operators will tell you what they think and will offer suggestions and recommendations. Getting that handshake going is an important part of what's going on right now.

LUNDQUIST: Do you also meet with and share information, data, and results of your experiments with allies or partner nations, such as the NATO Centre for Maritime Research and Experimentation (CMRE), or the Royal Australian Navy, or other science and technology organizations of like-minded nations?

HOUSTON: Yes. As a matter of fact, we've had a relationship with CMRE for a number of years and we've attended a lot of their workshops and participated in experiments and so forth. And the other international organization is The Technical Cooperation Program, which is a Five Eyes organization, where we meet, interact, and do projects with researchers from the Five Eyes nations—which includes the United States, Canada, United Kingdom, New Zealand, and Australia. That's also a very productive area for us, and there is a lot of work going on there.

LUNDQUIST: I've written about the Royal Australian Navy's SEA 1778 program [with the Defence Science and Technology Group], where they have adapted Bluefin-9s and -12s with Sonardyne Solstice sonars for expeditionary mine hunting.

HOUSTON: We have some familiarity with this. The capability of these systems is really very significant. Advanced imagery from the Solstice, coupled with the state-of-the-art classification software, and an ability to navigate underwater precisely is a valuable tool in shallow and very shallow water object classification.

LUNDQUIST: What else didn't I ask you that you wanted to say?

HOUSTON: The three branches of the acoustic division are contributing nicely to the Navy's evolving demands in undersea warfare. We're really proud of the work that our people are doing in all three branches, including the folks down at Stennis, who are focused on getting the Navy new technology with regards to how we deal with the environmental acoustics piece of the undersea warfare problem. There's a lot of involvement there in working directly with the fleet in getting them new technology, and that's a very exciting area in that we are capitalizing on years of research investment in ocean acoustics science part to create new technology that the fleet needs today.

About the author:

Capt. Lundquist writes on naval, maritime, and defense issues, including developing science and technology for warfighters.

About the interviewee:

Dr. Houston is the superintendent of the Acoustic Division at the US Naval Research Laboratory.

METEOROLOGY and OCEANOGRAPHY at NRL

By Nicholas E. M. Pasquini, Paul Cage, and Kevin McAndrews

SCIENTISTS AND ENGINEERS AT THE US NAVAL RESEARCH LABORATORY ARE INVOLVED IN A WIDE RANGE OF PROJECTS LOOKING AT WAYS TO OBSERVE THE OCEANS AND ATMOSPHERE MORE ACCURATELY.

Researchers Search for Critical Ocean Sciences Data with Lidar

US Naval Research Laboratory (NRL) researchers from the Ocean and Atmospheric Science and Technology Directorate along with the Scientific Development Squadron (VXS) 1's UV-18 Twin Otter recently conducted airborne research in Homer, Alaska.

The team's objective was to measure bubbles using lidar, a laser system capable of measuring ocean properties. Improved understanding of bubble fields has many applications, including radiance, surface properties, and characterization of the ocean's surface.

"We are characterizing bubble fields to help better predict the ocean environment for Navy operations," said Dr. Damien Josset, an NRL oceanographer and principal investigator of the project who conducted the experiments onboard the Twin Otter.

Quantifying oceanic whitecaps and subsurface bubbles is important to the Navy's oceanographic models to characterize the long-term evolution of the ocean environment because bubbles are the primary way the atmosphere and oceans exchange heat, momentum, and gas.

Current remote sensing techniques for ocean research rely primarily on passive observations at different wavelengths, including visible, infrared, and microwave, to estimate water leaving radiance and surface properties, such as sea surface temperature, salinity, and wind.

"Lidar is fundamentally different because visible light penetrates well into the water body and it has the unique capability to provide a vertical profile of ocean properties," Josset said.

NRL's lidar system consists of a self-contained unit installed in a weatherproof enclosure, designed to be mounted on the Twin Otter's research compartment with the laser pointed down toward the water.

Photo by Damien Jossett

The project required high surface winds to create bubbles, or breaking waves, and good flying weather.

"It's difficult to characterize the bubbles' vertical properties, especially at global scale, which makes lidar an ideal tool to measure the bubble structure and properties," said Josset.

The team deployed two underwater echo sounders and flew over the same area with the new airborne lidar system. The system was built with internal NRL basic research funding and is also a technology demonstrator for Josset's Office of Naval Research CubeSat and Department of Interior's Bureau of Safety and Environmental Enforcement oil projects.

"The goal is to test a small lidar that can provide high-resolution measurements of the ocean's physical properties and of oil thickness, in case of oil spills," Josset said.

"By improving the ability to characterize bubbly surfaces, improvements to ocean modeling and acoustic simulation can be achieved, as propagation can be significantly impacted by rough, bubbly ocean surfaces," Josset said.

Study Finds Localized Water Release in Upper Mesosphere Enables Cloud Formation

A team of scientists published an observational and modeling study showing that water vapor, a common launch byproduct of space traffic, can actively cool the mesosphere and induce the formation of polar mesospheric clouds.

Since the end of the shuttle age in 2011, 17 countries have created their own space agencies, now totaling more than 72, 14 of which have their own launch capabilities. In 2020, there were 104 successful rocket launches globally that potentially released water vapor. But what are the effects are these launches having on the earth's atmosphere?

"Nobody knows how much these smaller launches are contributing; not yet anyway," said Dr. Michael Stevens from NRL's Geospace Science and Technology Branch, and a paper coauthor. "If you're using these clouds to measure any small multidecadal changes, then they can become important. We've shown in this study that they could contribute significantly. But we don't know yet whether they actually do. This study has advanced our growing understanding of the impact."

Polar mesospheric cloud research at the edge of space serves to test high-altitude weather and climate models of the upper atmosphere that are important for the Navy.

"This new understanding of weather, including regions of the ionosphere, is critical for improving our understanding of high altitude radio signal propagation," Stevens said.

NASA funded the "Super Soaker Mission," a three-year study, which culminated with experiments in January 2018 at the Poker Flat Research Range in Alaska. The team created an experiment consisting of three sounding rockets: two rockets carried trimethylaluminum tracers, and a third rocket carried 485 pounds of liquid water.

While many American space missions launch in Florida, Poker Flat is a good location to study their effects in a controlled setting because of the ground-based instrumentation already in place there. Polar mesospheric clouds are at an altitude of about 53 miles and are thinner than the usual clouds one sees looking out the window.

The rocket with the water detonated, as planned, when it reached 53 miles altitude and within seconds, a ground-based lidar detected mesospheric clouds.

"The fact that we saw the clouds form so quickly and the fact that they persisted for about three minutes, was unexpected," said Stevens. "We saw it on screen and I don't think anyone in the room anticipated that."

A long-exposure view of the NASA "Super Soaker" rocket trail to its destination altitude of 53 miles, along with the lidar beam (green) used for temperature measurements and cloud detection. The launch was part of a NASA and US Naval Research Laboratory study showing water vapor, a common launch byproduct of space traffic, can actively cool the mesosphere and induce the formation of mesospheric clouds. Photo by NASA Wallops Flight Facility

Stevens was the sole NRL representative on the mission and he brought his previous experience with other case studies of this phenomenon conducted over the past 20 years.

"Polar mesospheric clouds appear in the summertime over the poles, and there is evidence they are getting more common. There are also several published papers showing main engine exhaust from the space shuttle can create these clouds, sometimes contributing up to 20 percent to a [mesospheric cloud] season," Stevens said. "Compared to the overall water budget of the Earth, of course, these contributions are negligible. But compared to the amount of water in these tenuous [clouds] it is not."

"You can only see [mesospheric clouds] near the polar latitudes with the naked eye when the sun is actually below the horizon but still shining up high in the atmosphere in front of you; that's how thin they are," Stevens said. "These altitudes where we're working are an arid portion of the atmosphere. So here we come, we launch a rocket full of water, and by detonating it, we're totally soaking this region. It's only a bathtub of water, but a bathtub up there is a big deal."

Stevens has spent most of his career working on satellite missions and said he felt privileged to work with such a great team at NASA and the Poker Flat Research Range science team.

"This was my first sounding rocket mission on which I was actively involved," Stevens said. "It was a different experience, and it was great, and I hope one day we can do it again."

A video of the 2018 rocket launches is available at http://bit.ly/3sBs12J. A video of a prelaunch interview is available at http://bit.ly/2Ph0jda.

Ocean Sciences Division Connects Research with Industry and Academia

NRL's Ocean Sciences Division at Stennis Space Center, Mississippi, has joined a broader Navy effort to connect scientific discovery with civilian industry and universities across the nation and beyond.

NRL joins the Naval Surface Warfare Center Panama City Division and the Naval Meteorology and Oceanography Command to form the new Gulf Coast Tech Bridge, which spans four states—Florida, Alabama, Mississippi, and Louisiana.

"Developing new partnerships with industry and academia will accelerate the transition of our science and technology for the benefit of the Navy, Marine Corps and the public," said research physicist Joe Calantoni of the Ocean Sciences Division. "We are excited about the long-term potential of this new venture."

An aerial view of sandbar features near Bay St. Louis, Mississippi. Researchers at NRL's Ocean Sciences Division study coastal features to determine how they evolve and impact coastal infrastructure. The division is a partner in the new Gulf Coast Tech Bridge. Photo by US Naval Research Laboratory

The Tech Bridge is focused on the future, growing coastal science and unmanned vehicle development, hosting industry events and expanding strategic partnerships. The Gulf Coast Tech Bridge's focus areas are: coastal sciences and technology, assured maritime access, and operational meteorology and oceanography.

"We want to enable our scientists and engineers to transform their discoveries into commercial products," Calantoni said.

NRL's Ocean Sciences Division conducts research in ocean physics, coastal remote sensing, coastal and seafloor sciences, and geospatial sciences. Researchers work to understand the complex interactions between the ocean and atmosphere through a combination of sensing and simulation.

Since the establishment last year of Tech Bridges under a Navy program called NavalX, the initiative has harnessed collaboration and creativity to address naval concerns and capabilities.

NavalX serves as the Department of Navy's research, development, and technology "super-connector" focused on delivering and facilitating rapid implementation of proven technology with high impact and broad applicability. Over the past year, NavalX has expanded the number of Tech Bridges to 15 across the United States and the United Kingdom.

Partnering with the Office of Naval Research and the Navy's systems commands, NavalX Tech Bridges connect, reinforce, and sustain regional innovation ecosystems in locations across the Navy. This enables collaboration with non-traditional partners, and develop partnerships that strengthen the Navy's operational capability.

Each Tech Bridge is supported by NavalX to seed early efforts until the Tech Bridge can stand alone with local partners. Current Tech Bridges are in the early stages of pilot projects designed to solve complex technological problems across the Navy.

Notable successes in the past year include funding $45 million in projects to solve naval problems, awarding more than $2 million in prize challenges to industry partners, sponsoring $37.5 million in Small Business Innovation Research targeting maintenance and sustainment, and helping to distribute more than $800,000 to COVID-19 response efforts.

About the authors:

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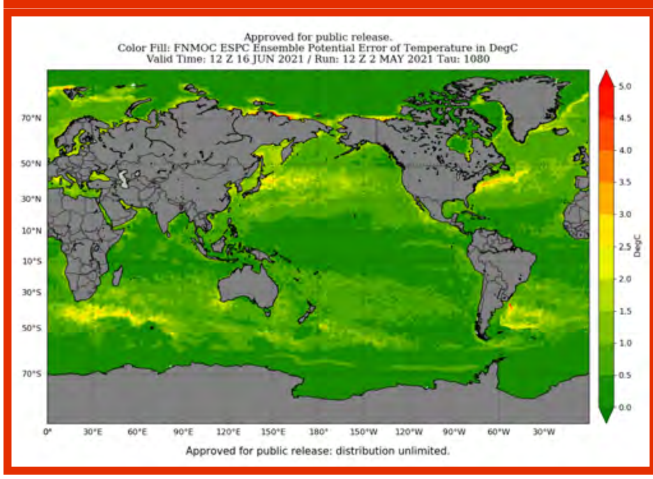
Navy Forecasting Provides 45-day Advanced Environmental Predictions

Earth's ocean-navigating environment just got a little less mysterious thanks to the US Naval Research Laboratory developed Navy Earth System Prediction Capability (ESPC) global forecasting system that went live in August 2020.

ESPC v1 provides the Navy with the first high-resolution ensemble capability for the ocean and sea ice that delivers both ensemble mean forecasts as well as a measure of uncertainty up to 45 days out.

"Atmosphere, ocean, and sea-ice conditions affect naval operations," said Carolyn Reynolds, a meteorologist at NRL's Marine Meteorology Division in Monterey, California. "The transition of this new system provides, for the first time, environmental forecast information that fills the gap between weather and climate timescales to advise decision makers."

Fleet Numerical Meteorological and Oceanography Center (FNMOC) released the new forecast system to provide these important program elements, and provide users a range of forecasts and an understanding of the accuracy of the forecast.



"Previously, global ocean and sea ice forecasts consisted of a single deterministic forecast out to seven days, but now Navy ESPC v1 provides an extended high resolution capability out to 45 days and the ensemble mean is typically more accurate than a single forecast," said Joe Metzger, a meteorologist at NRL's Ocean Sciences Division and project collaborator.

With Naval forces operating in dynamic environments around the world, having an accurate global long-range forecast provided by the Joint Typhoon Warning Center, Naval Oceanographic Office, and National Ice Center is critical to the safety of service members and for operational planning.

"ESPC is enabling higher-level Navy preparation for subseasonal-to-seasonal prediction," said Bill Kerr, the technical director at FNMOC. "For instance, knowing ahead of time the typhoon season in the Western Pacific will be particularly light or particularly heavy allows better force protection preparation and application of resources."

Kerr believes this initial implementation is just the tip of the iceberg for how ESPC will revolutionize environmental forecasting.

"The real payoff for this technology is still in the future, when ESPC becomes a rapidly evolving testbed for Navy R&D, and the same systems provide dynamically reconfigurable modeling capabilities in one coupled system for operations," Kerr said. "It's good now, but it's going to be game-changer for environmental forecasting."

Marine Corps Cpl. Peter Chang, a meteorological and oceanographic forecaster with 3rd Intelligence Battalion, prepares a weather balloon for flight during a training event at Kadena Air Base, Okinawa, Japan. Photo by Lance Cpl. Justin Marty

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