NAVAL SCIENCE AND TECHNOLOGY

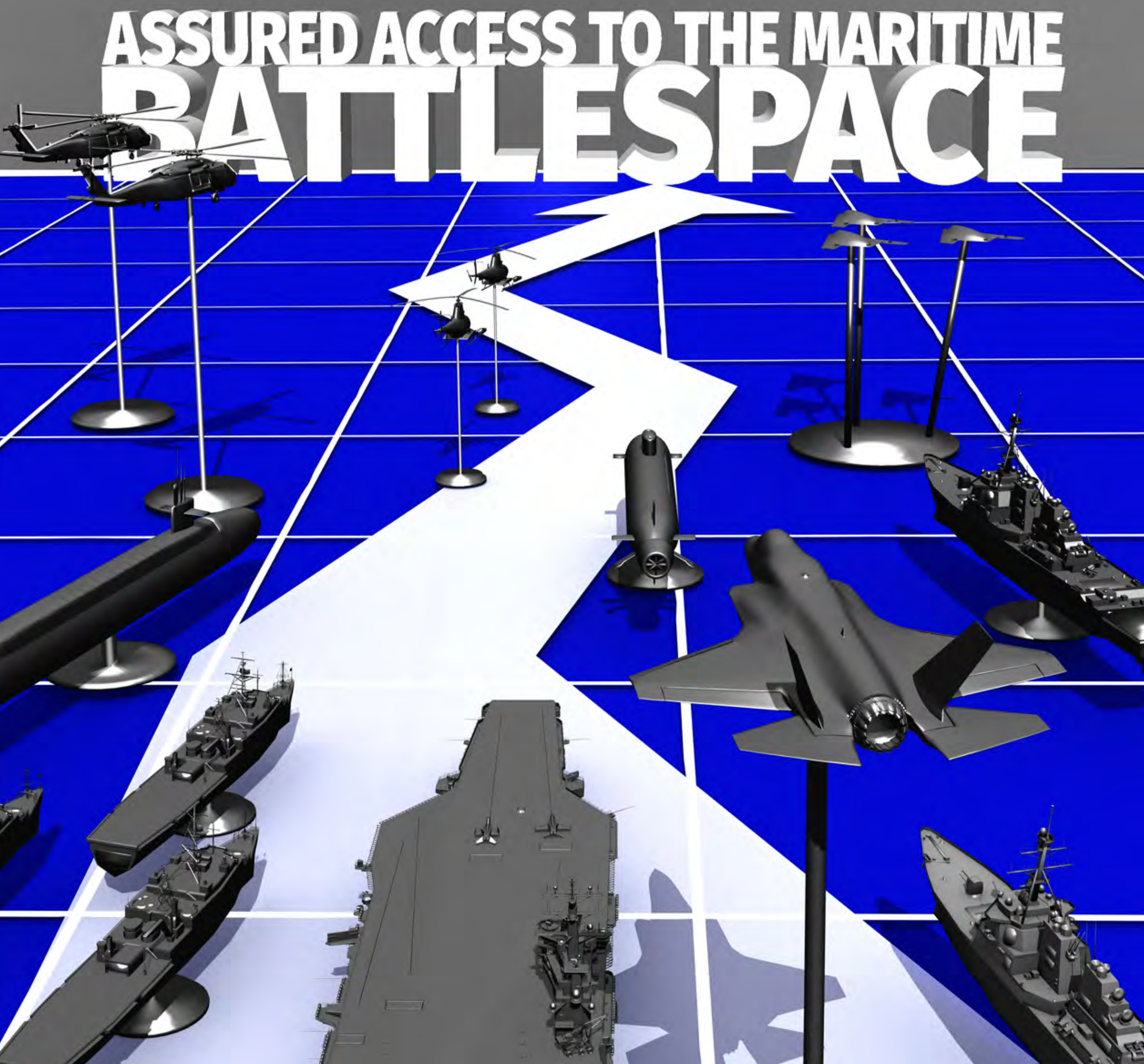
FUTURE FORCE™

WINTER 2016

WELCOME TO THE AGE OF LASER WARS

PREDICTING ICE AND WAVES

SENDING RADAR SIGNALS WITH LIGHT



VOLUME 3
#01
WINTER 2016

FUTURE FORCE

NAVAL SCIENCE AND TECHNOLOGY MAGAZINE

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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.

Front Cover: *The Last,* Illustration by Alvin Quiambao

For decades the United States enjoyed unfettered access to the world's oceans and littorals. Increasingly, our ability to assure global access to maritime, coastal, and riverine denied areas is challenged by both quantitative and qualitative improvements in the capabilities of potential adversaries. Assuring access requires the ability to enter into and operate in hazardous areas, to hold strategic, operational, and tactical targets at risk, to deny sanctuary to adversaries, and to improve operational performance by leveraging knowledge of the ocean environment.

This issue of *Future Force* focuses on the improvements to antisubmarine warfare, mine warfare, and naval special warfare technologies and capabilities that the Office of Naval Research is pursuing to assure access in support of US maritime operations. Underlying these improvements is a foundational understanding of the ocean-atmosphere-ice processes that impact naval operations. Our ability to predict the environment in denied areas using all available sensing modalities to inform decisions will allow the leveraging of a range of new technologies. The next decade will usher in a new era of autonomous sensors, both fixed and mobile. Autonomous underwater vehicles, which will potentially carry weapons at some point in the future, are rapidly maturing. New vehicles will leverage embedded signal processing and detailed physical environmental models to perform missions previously requiring manned submarines and other high-value assets.

The opening of the Arctic Ocean to surface navigation, the US strategic pivot to the Pacific, and global climate concerns all highlight the importance of the ocean environment. Satellite observations are increasingly available to both the military and civilian users. No longer can ships move unobserved. The opacity of the ocean long provided sanctuary, but gliding unmanned underwater vehicles and freely drifting low-cost sensors now paint a revealing picture of subsurface ocean features that may either cloak or reveal the adversary. The maritime battlespace of the future will be increasingly denied and contested, perhaps a great distance from coastal objectives. "Far forward" will take on a new definition, limited by energy, communications, control, and autonomy, among other key capabilities. This new era of undersea warfare will be driven by the advances in science and technology underway at ONR, and our ability to provide the fleet with advantages to ensure we facilitate the vision of no Sailor or Marine in a fair fight.

Dr. Drake is the director of the Ocean, Atmosphere, and Space Research Division at the Office of Naval Research.

ASSURED ACCESS TO THE MARITIME BATTLESPACE

Naval forces must be able to attain global access to denied areas. They must maintain the ability to penetrate and operate in hazardous areas, where others cannot. To accomplish this and provide access for friendly forces, assured access improves antisubmarine, mine and special warfare technologies and capabilities.

Above, the fast-attack submarine USS *Key West* (SSN 722) transits Subic Bay, Philippines. Photo by CS1 Christopher Rose

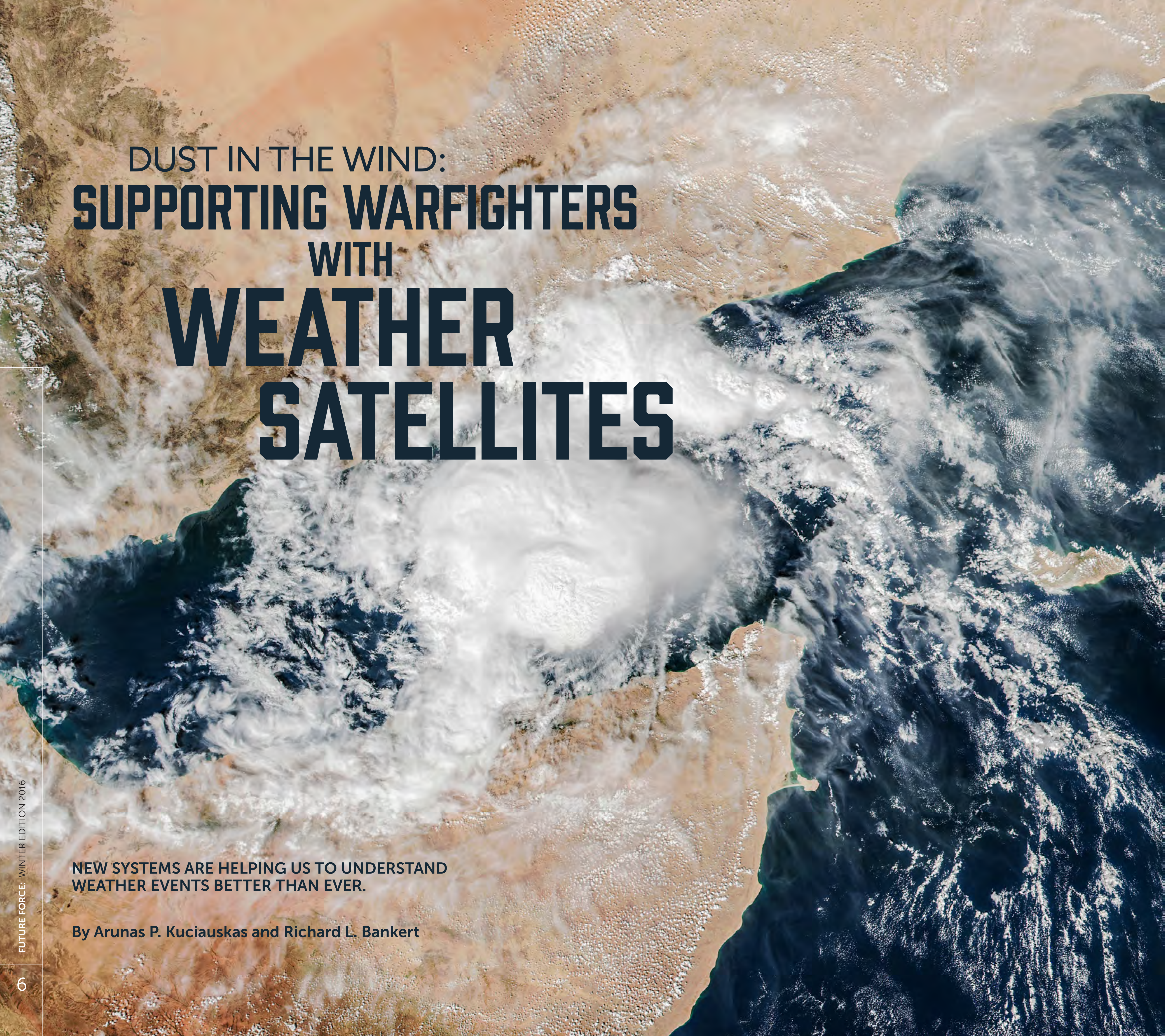


Photo by Jeff Schmaltz

DUST IN THE WIND: SUPPORTING WARFIGHTERS WITH WEATHER SATELLITES

NEW SYSTEMS ARE HELPING US TO UNDERSTAND WEATHER EVENTS BETTER THAN EVER.

By Arunas P. Kuciauskas and Richard L. Bankert

Since the mid-1990s, the Naval Research Laboratory Meteorology Division in Monterey, California (NRL-Monterey), has been at the forefront of weather satellite technology, developing algorithms for environmental characterization using data from sensors aboard low-earth-orbiting (LEO) and geostationary (GEO) weather satellite platforms. Through these algorithms, US Navy Meteorology and Oceanography Command (NMOC) forecasters have become equipped with a range of innovative new resources. During Operations Enduring Freedom and Iraqi Freedom, Monterey was responsible for developing multispectral satellite algorithms in near real time (within 1.5-hour product latencies) and on-demand Earth science data processing for both LEO and GEO sensors, in part to provide US and coalition forces with tactical decision aids related to daily operations.

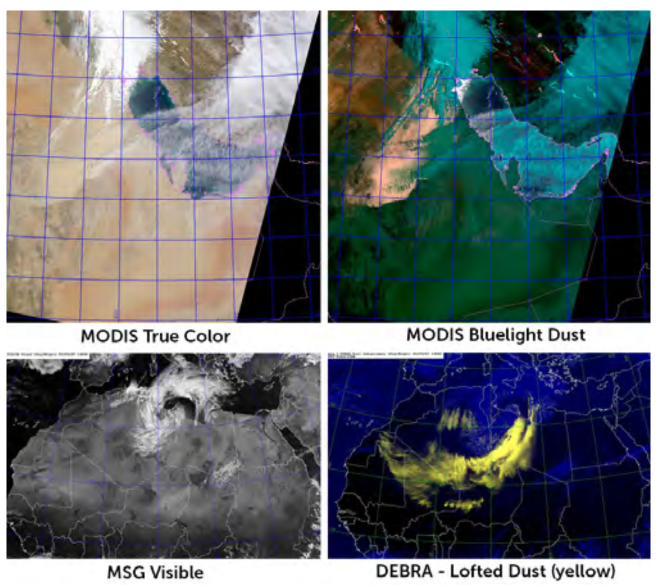
Meteorology and oceanography (METOC) forecasters had to deal with a number of distinctive environmental conditions common to the Middle East and Central Asia, such as:

- Lofted dust within desert terrain, which negatively affects ground-based maneuvers, electromagnetic/electro-optical instruments, flight operations, and smart weaponry
- Low cloud/fog conditions within the Arabian Gulf and surrounding regions that hampers shipboard operations
- Deep convective cloud systems that affects flight operations
- Increased aerosol optical depth levels over water that affect carrier operations
- Cirrus clouds that obscure low-level/surface targets
- Contrails that depict high-level flight patterns and possibly reveal vulnerable aircraft detection.

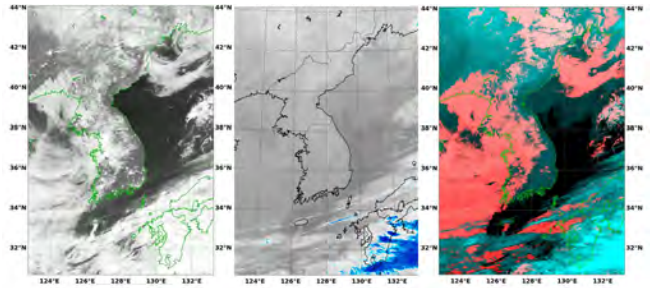
To fulfill this needs assessment, Monterey used the polar orbiting NASA Moderate Resolution Imaging Spectroradiometer (MODIS) instrument, consisting of a 36-channel suite of visible-through-infrared wavelengths with fine pixel detail, far superior to its LEO counterparts. A major challenge was to reduce the data latency (i.e., the time difference between the satellite data collection time and product time) with MODIS from nine to 11 hours, down to a more operationally relevant range (under an hour and a half), thanks mainly to NRL-Monterey strong partnerships with US government and academic agencies that include the Air Force, NOAA, NASA, and the Cooperative Institute for Meteorological Satellite Studies at the University of Wisconsin-Madison.

To provide users with GEO support, starting in 2004, NRL-Monterey acquired calibrated datasets from the first of a series of technologically enhanced GEO satellites (the Meteosat Second Generation, or MSG) launched by the European Organisation for the Exploitation of Meteorological Satellites. Similar to MODIS, MSG provided significantly improved sensing capabilities compared to other GEO instruments. The advantage of MSG is a new image is available every 15 minutes. There are a host of other available LEO and GEO sensors and associated image products that augment the entire scope of environmental sensing.

With applied research funding, NRL-Monterey used a combination of both MODIS and MSG datasets to develop imagery during operations in Afghanistan and Iraq. Initially, the products were restricted for research, development, and demonstration purposes only, residing in web-based platforms but only within a pseudo-operational environment. This limited status hampered operations to METOC forecasters situated in the Middle East because the bandwidth was limited (especially aboard ships) and the data processing and image production was typically not monitored 24/7. In partnership with its on-campus neighbor



The top image pair compares the MODIS-derived true color (upper left image) and the "blue light" dust enhancement (upper right image) products. The dust signature appears in shades of orange, while the cloud fields appear in green and teal shades. The bottom image pair compares the MSG visible (lower left image) with the Dust Enhancement Background Reduction Algorithm (DEBRA) dust product (lower right image). As illustrated, dust is very difficult to discern with visible or true color, but is easily distinguished from the background environment, even within the bright desert terrain and cloud field.



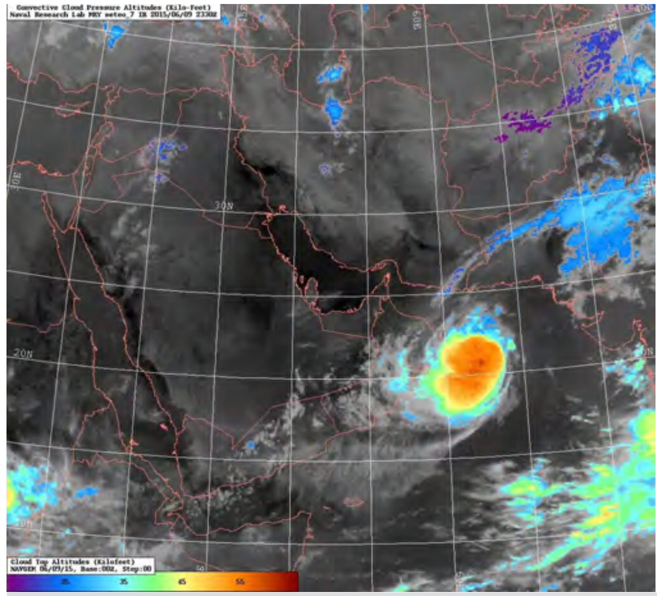
The set of corresponding night time views of VIIRS-derived low light visible (left), infrared (center), and low cloud (right) products centered over the Korean peninsula. The latter product depicts low clouds within red/pink shades.

at the Fleet Numerical Meteorology and Oceanography Center (FNMOC), the process of product transition and operational development began in 2004. By 2006, FNMOC processed and hosted the products into the Navy Enterprise Portal website. This portal provided near-real-time weather satellite support geared toward global operations.

Currently, a new generation of satellites is well under way with the launch of the NASA/NOAA Suomi-National Polar-orbiting Partnership (S-NPP) LEO platform in October 2011, which is the first of the Joint Polar Satellite System. S-NPP carries the Visible Infrared Imaging Radiometer Suite (VIIRS), offering 22 spectral channels ranging from visible through thermal infrared, with significant technological advances compared to older sensors. VIIRS is designed to improve detection in cloud and aerosol properties, ocean color, sea and land surface temperature, ice motion and temperature, fires, and Earth's albedo. Some of the significant improvements of VIIRS over its predecessors include finer spatial detail across a broader scanning swath, low light capabilities for nighttime viewing, and increased radiometric fidelity resulting in better intensity discrimination between pixels. Leveraging the research performed with MODIS data allowed for the quick development and demonstration of product algorithms to characterize the environment through VIIRS data.

The next generation of GEO satellites commenced in October 2014 with the Japanese Meteorological Agency's launch of the Himawari-8 satellite. This satellite carries the Advanced Himawari Imager (AHI) and is similar in design to other international program GEO missions planned for launch in the coming decade. One of the major advantages of AHI over MSG sensors is the former's significantly improved temporal resolution.

NRL-Monterey will continue to research, develop, and demonstrate the capabilities of next-generation sensors, including currently available retrievals from S-NPP VIIRS and Himawari-8 AHI. The illustrations in this article represent a sampling of image products showing some of the METOC-requested products listed above that were developed at NRL-Monterey. Starting with Himawari-8 AHI sensor data, NRL-Monterey is continuing the research, development, and demonstration of LEO and GEO sensor data algorithms as the data become available, leveraging previous algorithm development using MODIS, VIIRS, and MSG datasets. NRL-Monterey is making the necessary software and hardware upgrades to ingest, store, and process massive data sets once they become available. NRL-Monterey will apply its expertise in algorithm development as well as leverage



Meteosat-7 derived cloud top altitude "convective" product depicts a strong tropical cyclone within the southern Gulf of Oman. Cloud top heights greater than 20,000 feet are colorized to locate the colder and typically more active (convective) part of cloud fields. This product allows users to focus quickly on the more active cloud aspects and alert pilots of potentially hazardous conditions.

technological developments from outside agencies. As a result, there will be a plethora of new products to assist the METOC community (forecasters, strategic planners, and air- and surface-based warfighters), with all products planned for transition to operations at FNMOC. Although the Navy Enterprise Portal website will continue to provide operational support for the satellite products described here, the NRL-Monterey Satellite METOC website will be used in the future as testing and demonstration vehicles for products developed through the exploitation of the data from these future sensors.

Tentative Launch Dates of Upcoming Weather Satellites

There is a suite of upcoming GEO and LEO platforms with similar sensing capabilities. The launch schedules for upcoming next-generation US and European satellites are:

2016

a – GOES-R
(US NOAA/NASA)

2017

b – GCOM-W2
(Japanese Aerospace Exploration Agency)

2018

c – Earthcare
(European Space Agency)

d – GEO-KOMPSAT-2A
(Korean Meteorological Administration))

e – GOES-S (US NASA/NOAA)

f – METOP-C (European Space Agency)

2019

g – Meteosat Third Generation
(European Space Agency)

h – GEO-KOMPSAT-2B
(Korean Meteorological Administration)

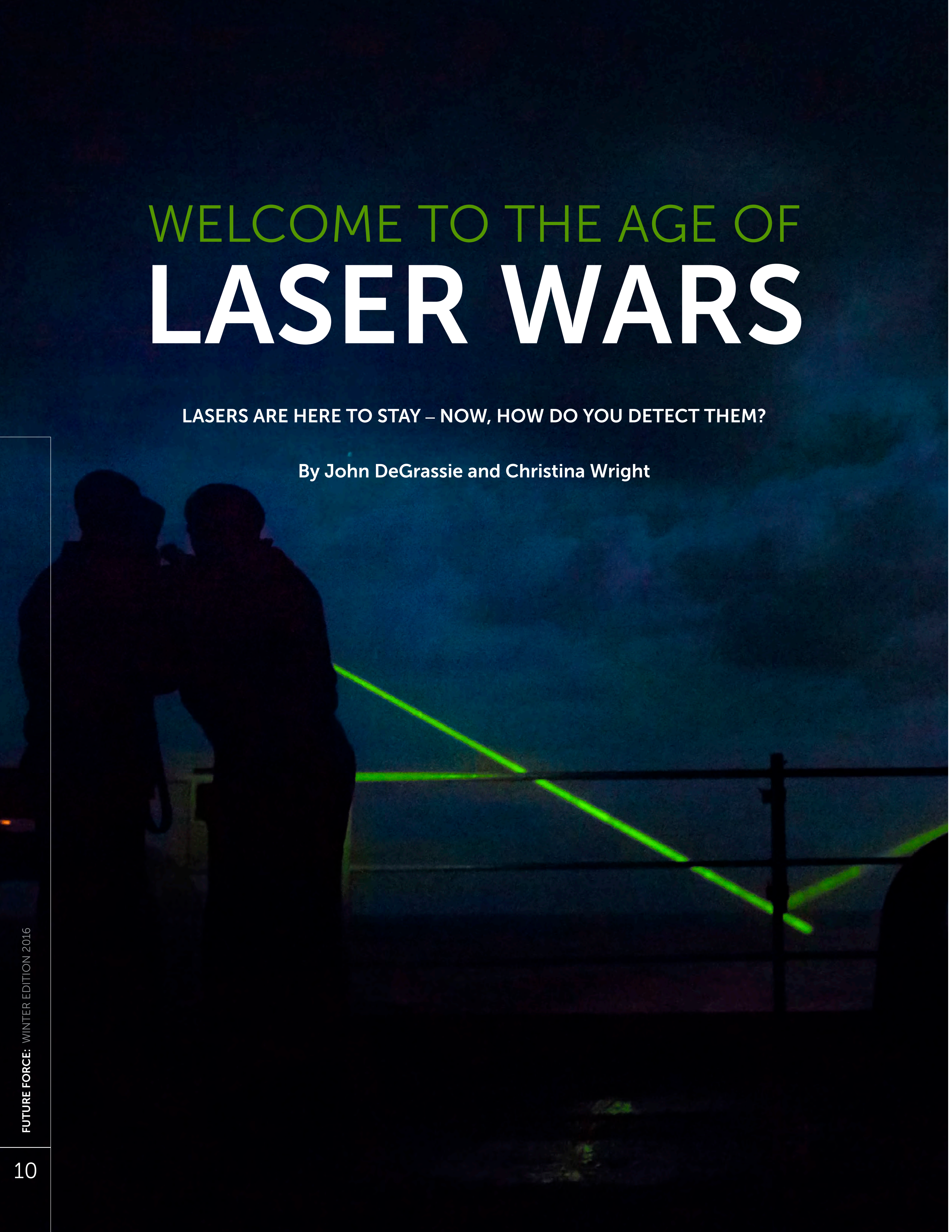
2021

i – JPSS-2 (US NOAA/NASA)

NRL-Monterey plans to acquire these datasets to develop next-generation environmental characterization algorithms. For further information and updates on the satellite missions described above, go to: http://www.wmo-sat.info/oscar/satellites.

About the authors:

Arunas Kuciauskas and **Richard Bankert** are research meteorologists with the Naval Research Laboratory Meteorology Division's decision systems section and both manage the website hosting processed weather satellite products.



WELCOME TO THE AGE OF

LASER WARS

LASERS ARE HERE TO STAY – NOW, HOW DO YOU DETECT THEM?

By John DeGrassie and Christina Wright

Photo by MC3 J. R. Pacheco

The recent at-sea tests of the Navy's Laser Weapon System have ushered in a new era—the age of "Laser Wars"—where there is an increasing role for directed-energy weapons in the battlespace. How will commanders detect, assess, and counter laser or laser-assisted threats in this new operational environment to protect warfighters and ensure mission success?

Lasers engage at the speed of light, effectively point-to-point along the line of sight, at wavelengths usually not visible to the human eye. This means that the laser systems entering this era have a low probability of being detected and intercepted.

A current laser warning receiver (LWR) that detects laser or laser-assisted threats relies on direct or near-direct illumination by the laser. This may be sufficient to protect individual Navy assets against a laser threat, but will be insufficient to meet the spectrum dominance and battlespace awareness that the new era of "Laser Wars" demands.

For example, to protect larger Navy assets (protecting a group of landing craft from laser-guided mortars or protecting Navy ships in foreign ports from laser threats) the current LWR capabilities will not scale practically.

Laser tracking or engagement attempts by hostile systems are point-to-point and therefore have a high degree of specificity when targeting. For small assets where LWRs can be located near critical targets, the LWR may effectively detect a laser threat. On the other hand, a large Navy asset like an aircraft carrier or groups of assets would require many LWRs to guard fully against potential threats. Perhaps more than 30 existing sensors, for instance, would be required to guard an aircraft carrier against potential laser threats. This could be cost prohibitive and would be extremely difficult to maintain.

In addition, to meet the battlespace awareness demands in an environment where lasers are present, lasers need to be detectable from reconnaissance platforms that are far away from the engagement.

To overcome the scalability problems with current LWRs and to enable greater spectrum dominance through increased battlespace awareness, a new laser detection capability that can detect indirect laser illumination is needed—an "off-axis" laser detection capability.

Space and Naval Warfare System Center Pacific's (SSC Pacific) Atmospheric Propagation Branch is developing such a capability with the Laser Identification through Scattering and Beam Recognition (LITSABR) project. This effort supports counter directed-energy weapons (CDEW) efforts and intelligence, surveillance, and reconnaissance capabilities. LITSABR is currently being supported by the Office of Naval Research's CDEW discovery and innovation program.

Detecting lasers at positions far from direct illumination is a difficult problem to solve; it requires a diverse set of expertise, including accurate atmospheric modeling, precise atmospheric characterization, sensor engineering, and careful laser physics modeling. Recognizing this, a variety of expert performers is collaborating to address the off-axis laser detection problem. They include the Naval Research Laboratory, with experience in high-energy laser physics and aerosol physics; the Naval Academy, with experience in laser propagation and energy absorption; the Georgia Tech Research Institute, with its one-of-a-kind lidar for precise atmospheric profile measurements; Nanohmics, Inc. and Sensing Strategies, Inc., with experience in designing sensitive laser detectors; and SSC Pacific and its LITSABR project.

DETECTING LASERS AT POSITIONS FAR FROM DIRECT ILLUMINATION IS A DIFFICULT PROBLEM TO SOLVE; IT REQUIRES A DIVERSE SET OF EXPERTISE.

How Does It Work?

If you have ever attended a music concert that employed fog machines and lasers to enhance the musical experience, then you know the basic fundamentals involved in off-axis laser detection.

The principles of how a laser beam can be detected off-axis are demonstrated when the colored laser beams pass through the fog-like substance at the concert and some of the laser light is scattered at an angle to its original line (or axis) of propagation toward off-axis observers, in this case the audience. The key process is the scattering of the laser light by a given medium: the fog in the laser light show. This redirects the laser signal, allowing it to be detected by the off-axis sensors, the eyes of the concert attendees in the audience. Without the presence of the fog medium, this would not be possible. The lasers would need to be pointed directly or nearly directly at the audience to be seen.

In the same way as the fog in the light show, particles in the atmosphere (molecules, aerosols, dust, soot, etc.) will scatter propagating laser energy of all wavelengths, visible to the human eye or not, into directions not collinear with the original line of propagation. Scattered laser energy is, in principle, detectable with a sensor or camera with adequate sensitivity at the wavelength of the laser light of interest--though the number of atmospheric scatterers is typically fewer than in the concert fog example and results in less scattered light. Nevertheless, the resulting scattered laser energy can enable laser warning receivers to detect and identify laser threats from positions that are far askew from the laser's directed path of propagation. Scattering is always present to some degree in the atmosphere, even on clear days, and depends on the propagation geometry, location, time of day, time of year, and local weather.

With the Atmospheric Propagation Branch's expertise in modeling the laser propagation environment, the LITSABR project is providing predictive models to aid in the design of future sensors and to help inform tactical decisions on the use of those sensors and related laser technologies. Knowledge gained from the program will be critical to answering where and when a laser is detectable by a given off-axis LWR.

In addition to the atmospheric modeling, the LITSABR project is developing an off-axis laser detection and characterization capability using multistatic imaging sensors. The LITSBR project builds on research carried out in the Bistatic Laser Detection at Large Standoffs (BLDLS) project, a prior ONR CDEW-funded program. The system works by combining images of the scattered laser light taken by multiple cameras. From these images, the laser position, direction, and other characteristics can be determined. The technique is similar to 3D scene reconstruction from imagery used in computer vision research to create representations of buildings and topography. For the LITSABR capability, the multistatic off-axis detector reconstructs the 3D representation of the detected propagating laser.

The multistatic capability requires multiple cameras to take a single image or images of the scattered laser beam from multiple vantage points. Multiple images are necessary for depth perception since, with all other variables held constant, one image or vantage point cannot distinguish points that are far away from those that are near, thus the distance from the camera to the laser cannot be determined. The position of any single camera and the line delineating the laser beam axis define a plane in space called an "ambiguity plane." On this plane, many different beam axis distances (locations) and orientations (propagation directions) will provide the same image projection to the camera, leaving the laser position and orientation uncertain or ambiguous without any additional information.

Introducing a second image or vantage point can break this ambiguity just as binocular vision provides depth perception. The position of a second camera and the laser beam axis define a second ambiguity plane in space. The two nonparallel ambiguity planes intersect in a line. The line in which the two camera-laser axis ambiguity planes intersect gives the actual orientation of the laser beam in space. Once the 3D coordinate representation of the laser is determined, the laser origin and direction is readily determined. The feasibility of using two cameras to detect and characterize a laser from images of the atmospheric scattering was demonstrated in the BLDLS project.

The LITSABR project is currently pursuing a multistatic sensor approach, using three or more sensors. Introducing additional sensors improves the effectiveness of the system, allowing the laser source to be located even for special cases when two cameras leave some ambiguity. It may also improve the accuracy of the laser location for cases when the atmospheric scattering is weak or inconsistent.

The multistatic approach also reduces the error in a bistatic measurement. With more camera-laser axis ambiguity planes this uncertainty can be reduced, and the LITSABR project already has demonstrated reduced errors with this method.

Using three or more sensors in the multistatic off-axis laser detection approach not only overcomes degenerate cases but anticipates a distributed network of sensors in the battlespace. With the multistatic approach the LITSABR capability can use existing sensors, systems, and imagery to create an off-axis laser detection capability

Photo by John F. Williams

The Navy's first operational Laser Weapon System was deployed aboard USS *Ponce* (AFSB[I] 15). More, and more powerful, lasers are primed to follow.

with little additional cost. This approach can meet the demands of the new operational environment and grow organically along with other sensing capabilities by using any and all available imagery of scattered laser light. With a few off-axis LWRs or using existing deployed sensors or both, the capability developed in the LITSABR project, in conjunction with other CDEW programs, can provide an off-axis laser detection capability cost-effectively.

Bringing Lasers to the Fleet

The Navy is currently developing and testing a demonstration shipboard high-energy laser weapon, signaling an ever-growing role of lasers in naval operations. To counter any similar laser threats to its own operations, it is critical that the Navy has capabilities for early detection and characterization of laser threats. The LITSABR program enables this capability, enhances national security, and helps ensure the Navy can operate in an increasingly complex electromagnetic and electro-optical environment. The difficult challenges to realizing off-axis laser detection are being addressed and will enable greater situational awareness in today's maritime battlespace.

The LITSABR program has demonstrated multistatic off-axis detection and characterization, incorporating more than two cameras, at the proof-of-concept level. Atmospheric models will need to be integrated with the multistatic capability and validated through outdoor atmospheric experiments. Once baselined, the models developed with the LITSABR and collaborative programs then can be used to validate other off-axis LWRs, and inform countermeasures utility decisions for laser threats. This is one area where collaboration with other Navy programs is most critical. Pulling together the best expertise and resources is absolutely necessary for off-axis LWR modeling and sensors to be validated.

In addition, the LITSABR program is planning to apply the multistatic capability to single, moving imagers and "swarms" of imagers in both real time and after analysis to make platforms into sensors for laser threat detection and characterization.

As lasers grow in civilian and military operations around the world, it is critical that any lasers present can be detected and characterized in order to assure access to the battlespace. With capabilities like those developed under the LITSABR program, warfighters have a method for detecting and characterizing lasers from off-axis standoff ranges far from direct laser illumination to enable and inform CDEW technologies.

About the authors:

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TWELVE DAYS BEFORE THE MASTT

THE MOBILE ANTISUBMARINE TRAINING TARGET MIMICS THE QUALITIES OF A FULL-SIZED SUBMARINE

By J. Overton

Gaining access to all operational domains has been a goal of naval operations for a long time. The US Navy's first ship loss as a result of enemy submarine attack came from an attempt to prevent all domain access, in this case, access to Charleston harbor off South Carolina. On the night of 17 February 1864, the small human-powered Confederate submarine *H.L. Hunley* managed to approach the US sloop of war *Housatonic,* anchored in the harbor, and attacked it with a spar torpedo. *Housatonic* sank, as did *H.L. Hunley*, by accident. While the action had little decisive impact on further U.S. operations in Charleston or on the outcome of the Civil War itself, it did present a new challenge to the ability of ships to operate freely at times and places of their choosing. Dangers from the undersea environment had always been one of a mariner's greatest fears: rocks and shoals, the occasional outsized and angry marine mammal or fish, and, by the 1860s, the potential danger of naval mines (or "torpedoes" as they were originally known). A piloted submarine ship, however, was a far different type of threat. There was little a merchant or naval ship could do to counter such a platform, and operations in any body of water where a hostile submarine could lurk would always come with some level of hesitancy and added caution.

The sinking of *Housatonic* began a new era of warfare. Within 50 years the submarine would have a strategic impact during the largest conflict the world had experienced, and a submarine action by the Central Powers would draw the United States into the war on the side of the Allies. Starting with World War I and continuing to the present, the most effective means our enemies used for challenging American forces access to a maritime battlespace has been the submarine. Certainly mines and natural obstructions took their toll, from the beaches of Normandy to Inchon Harbor and the Persian Gulf, but static devices lack the maneuverability provided by a submarine. Controlled by humans, they are able to react and adapt, rather than simply await contact. And largely because of that human element, they're still very difficult to find, detect, and mitigate.

Train Like You Fight

For as long as submarines have been a threat, navies the world over have tried to find better ways to train to counter them. Few good choices have existed for accurately portraying an enemy submarine: actual submarines have been used (such as decommissioned boats that were simply towed), as have unmanned undersea vehicles (such as small, highly-computerized devices that mimic enemy submarine actions and signatures). Both methods have their drawbacks, be that expense, lack of deployability, artificiality, or a combination of all three.

The Mobile Antisubmarine Training Target (MASTT) is the latest step in the century-and-a-half-long quest to train for antisubmarine warfare (ASW) the way it is actually fought. This vehicle can be operated with just a few off-board crew members, is transportable, and more realistically mimics the look and characteristics of a submarine.

MASTT Meets the Fleet

Built using commercially available technology, MASTT is an 80-foot-long, 60-metric-ton unmanned underwater vehicle that, as its name implies, can be transported relatively easily to wherever the fleet needs it for ASW training. It has been an asset of Naval Undersea Warfare Center Keyport's San Diego detachment since 2012, undergoing testing and evaluation to prepare it for regular operations. The final step in that process was a fleet assessment, completed successfully during 12 days in September 2015 at the Southern California Offshore Range near San Clemente Island.

During the 12-day assessment, MASTT operators and support staff ran it for a total of 20 hours and 51 minutes, both surfaced and submerged. MASTT performed its longest submerged missions to date at five and seven hours, its longest surface operation at 15 miles, and its longest tow at 30 miles. MASTT was operated by two three-person control teams working in four-hour watches from the range craft cruising near MASTT. These runs were interspersed with time for the MASTT team to evaluate progress, make adjustments, and do preventative maintenance. "This was the first time MASTT was operated without original equipment manufacturer support," said NUWC Keyport's test director for this assessment. "The team demonstrated the ability to independently operate, maintain, and troubleshoot the MASTT system while at-sea. They also showed they could rapidly reprogram the vehicle and change run parameters to meet customer requirements."

Those customers included a guided-missile destroyer, which participated for two days of the assessment, and a P-3C Orion aircraft, which participated for one day. The ship and aircraft were able to practice tracking MASTT as they would a real submarine and MASTT was able to prove its worth to fleet ASW training.

Maintaining Undersea Dominance

Following the conclusion of scheduled tests, MASTT and support staff returned to San Diego to analyze the assessment, document lessons learned, and reflect on their accomplishments. "The MASTT team overcame a number of challenges in a remote location with limited reachback," said the test director. "It was only through their ingenuity, technical expertise, and perseverance that Keyport and MASTT were able to be as successful as they were."

Just as the Confederacy did 150 years ago, nations and non-state actors will increasingly seek the asymmetrical capability provided by submarines and other underwater craft. With limited range and strike capability, they will now, as then, be used often to control seas in the near-shore environment, and potentially deny access and operational freedom to others. Countering this condition is one of the primary functions of U.S. sea power, and MASTT is a new and vital tool to help the U.S. Navy and our allies keep all areas of the maritime domain free and accessible.

MASTT Launches, Operates, and Recovers

About 20 people were on the MASTT team for this assessment, including engineers, technicians, divers, and boat operators. Once in the vicinity of the desired operating area, MASTT was checked by technicians and engineers while still in its customized cradle aboard the barge. A crane on the anchored barge then lifted MASTT and lowered it into the water. Navy divers from the Keyport Dive Locker, working from rigid-hull inflatable boats, unhooked MASTT from the crane lines. Crew members on the nearby tug boat affixed a tow line to MASTT's bow and towed it to the operating space.

MASTT was operated by a three-person team consisting of an engineer, an operator, and a log keeper, filling at least some roles of the shipboard bridge positions conning officer, helmsman, and quartermaster, respectively. While it was still under tow, this team, working from the nearby range craft, their portable control equipment set up on the craft's bridge, checked to see that MASTT was ready to go under its own power. Once assured that all was well, the control team communicated to the tug crew that MASTT could be untethered. They then dictated a course to demonstrate it was operating properly and could perform as needed.

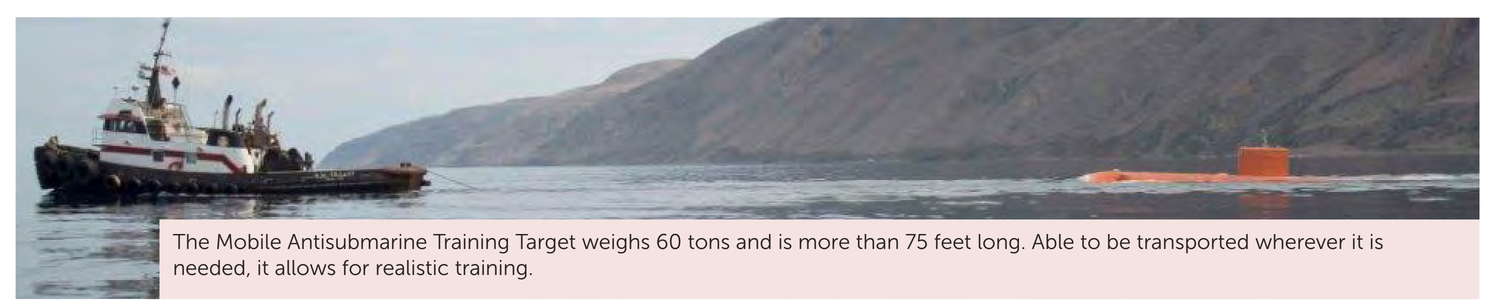
With this initial cruise complete, it was taken back under tow and returned to its barge. There the divers reversed their earlier evolution, easily re-securing crane lines to MASTT for it to be lifted out of the water and placed back aboard the barge for maintenance checks.

Similar control exercises were done during the fleet assessment to demonstrate the array of MASTT's capabilities and ability to interact with other vessels.

About the author:

J. Overton is a public affairs writer/editor with Naval Undersea Warfare Center Keyport Division

Photos courtesy of NUWC Keyport



The Mobile Antisubmarine Training Target weighs 60 tons and is more than 75 feet long. Able to be transported wherever it is needed, it allows for realistic training.

FORWARD OPERATORS NEED ADVANCED ENVIRONMENTAL SUPPORT

FULL STEAM AHEAD?
BETTER ENVIRONMENTAL SUPPORT LEADS TO BETTER DECISION MAKING.

By Capt. Tony Miller, USN, and Dr. K. Todd Holland

Photo by MC2 Liam Kennedy

As the operational arm of the Naval Meteorology and Oceanography Command (NMOC), the Naval Oceanography Operations Command (NOOC) provides meteorology and oceanography information to warfighters. NMOC production centers are engaged in sensing, characterizing, predicting, and assessing the effects of the physical environment. In addition to embedding teams within operational decision makers' staffs, NOOC provides meteorology and oceanography support to forward personnel through a reachback approach. This concept of operations is therefore two-fold: with small-footprint, forward-deployed teams working with the warfighters, and with associated reachback to NOOC watch floor personnel with more substantial technical capabilities.

This concept provides a unique opportunity to investigate possible approaches to the sensing, modeling, and decision-making cycle that forward-deployed teams require. Since the Depot of Charts and Instruments (the forerunner of both the US Naval Observatory and the Naval Oceanographic Office) opened in 1830, forward-oriented commands have collected ocean measurements. For example, when Lt. Matthew Fontaine Maury arrived as head of this command in 1844, he began to glean from ship's logs (both naval and merchant marine) all manner of environmental information, to catalogue the data, and to use it to produce charts of currents, prevailing winds, sea-life feeding areas, and other assorted weather and oceanographic information useful to mariners. Over time, this focus has greatly expanded within NMOC commands to sensing global environmental data, organizing and storing databases that have resulted in extensive climatologies, and using oceanographic and atmospheric numerical prediction models at multiple spatial and temporal scales. The current scope of meteorology and oceanography support includes every warfare mission area, but only recently has NOOC developed a formal approach for the use of forward-sensed data in rapid decision making, especially for areas that are difficult to access physically.

In collaboration with the Naval Research Laboratory, NOOC has made significant progress in its support of naval special warfare and antisubmarine warfare under the two-fold concept of operations. Two current applications are discussed here.

Traditionally, forward support products are based on databases and models produced by the reachback cell in advance to provide relevant information needed by Navy warfighters in their decision-making cycles.

NMOC has recently begun to employ a wide range of ocean sensors to supplement the flow of environmental information. For example, under the drifting buoy program, at any given time, the Naval Oceanographic Office has approximately 23 drifting buoys deployed around the world. In addition, through the Argo program, the office has access to observations from 1,350 buoys deployed by universities, other government agencies, and foreign countries. All these buoys measure sea surface temperature; smaller subsets of buoys measure some combination of sea level pressure, surface wind, surface salinity, and even currents. These observations are vital to enhancing the Navy's ocean prediction skill, but they also provide data directly to forward operators to continually verify model predictions supporting their decision making.

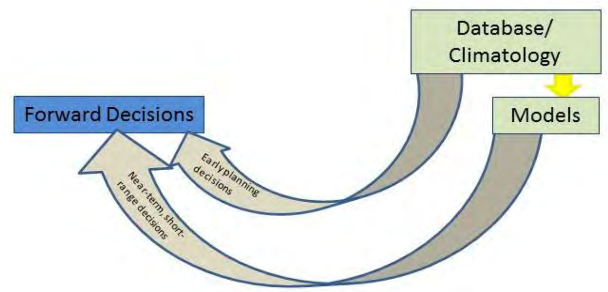
Profiling floats also add a level of sophistication to ocean data collection. The Naval Oceanographic Office has 124 of these floats deployed, primarily in areas of high Navy interest, and has access to approximately 3,500 other floats worldwide. These devices are more complex than the drifting buoys, with a floating buoy at the surface and a probe that is lowered and raised through the water column to collect data at various depths down to 2000 meters. The floats are highly valuable in improving model accuracy by providing temperature and salinity data throughout the water column instead of just at the surface. In addition, these floats can provide an indication of subsurface currents at the depth where the probe is parked when not profiling.

Gliders, though limited to speeds of about a half knot, are under the direct control of the Glider Operations Center and can be steered to where most needed. They collect the same temperature, salinity, and depth data that conductivity, temperature, and depth (CTD) devices deployed from survey ships do and they can be equipped with additional water column sensors either on the body of the glider itself or towed behind it.

As naval platforms operate forward, they also are constantly sensing the environment around them. This comes from a variety of sources, including measurements made by the platforms, weapons, and weapon sensor systems themselves. In addition, when deployed meteorology and oceanography teams are embedded with warfighter staffs, they are taking dedicated environmental observations useful to other teams as well. This data can be used to inform revised decisions made on the scene as an operation begins and progresses.

One example of forward sensing is the collection of ambient noise data through the sensor. Many Navy sonar systems measure ambient noise as they operate. In most of the world's oceans, ambient noise can vary significantly by location, season, traffic density, weather, and even time of day, so measured ambient noise will yield much more accurate results than information from climatological databases. These measurements are used on scene by operators to make decisions in tuning the equipment for most effective performance.

This is typically where the decision process stops (as shown in the figure below). Any ongoing support from the reachback cell is produced without the benefit of observations collected forward. The aim of the current projects is to complete this loop by feeding environmental data sensed forward to the reachback cells and production centers to validate previous model output and reduce uncertainty in future model output. Since starting a model with more accurate initial conditions results in more accurate model predictions, the second objective is to use the data sensed forward in the reachback cell to provide more accurate support to the deployed teams forward, and ultimately, to warfighting decision-makers.

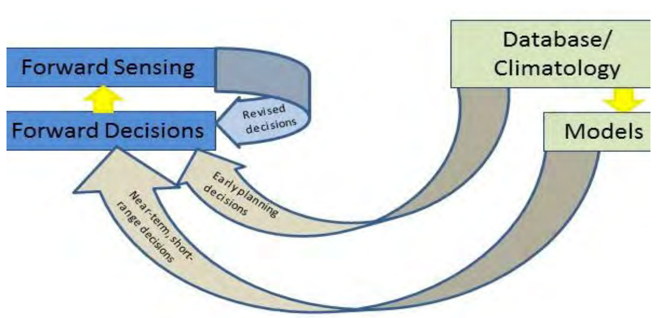


Decision Making Using Shore-Based Inputs

While the original intent of observation capabilities of shipborne sonars was to tune the sonar itself during operation, when those observations are fed back to the reachback cell, updated predictions can be made that allow for better environmental support and, ultimately, better decisions. This concept can be extended beyond just ambient noise, as antisubmarine-capable ships at sea also measure reverberation and other information such as sensor operating mode, tow depth, and detection ranges. All of these observations would significantly enhance the reachback cell's ability to provide accurate environmental support for antisubmarine warfare if those data were routinely passed to the reachback cell. By using the more accurate baseline for both sensor lineup and the physical environment that is enabled by these data, the reachback cell is able to provide more accurate model results and tactical recommendations.

A related example of extended observational capability comes from unmanned underwater vehicles, the most controllable of all observation platforms, which are deployed on scene to collect observations exactly where warfighters need them and can be driven to speeds of four knots or greater. In addition to the normal water column data such as temperature and salinity, they are equipped with acoustic Doppler current profilers to measure current speed and direction very accurately. They can survey the bottom depths with single-beam or multibeam sounders. Both this accurate current data and high-fidelity bottom bathymetry allow significant improvements in the accuracy of littoral ocean models that are vital to supporting special warfare missions. They also are equipped with side-scan sonar that can provide a wealth of information on bottom type and clutter as well as build historical databases that can be compared against new surveys to shorten the timeline in minehunting.

The normal process for using environmental information in warfighter decision making normally follows the path outlined below; completing the loop as in in the figure at right is rare. NOOC's goal is to make the latter approach the normal way of doing business for all environmental support. Two efforts are currently under way to demonstrate this more advanced loop of sensing, databasing, modeling, and decision making.



Environmental Sensing Informing Decisions

Antisubmarine Warfare

Even though ambient noise and reverberation are measured by sonars at sea, there has never been a reliable communication path to provide that data nor the sensor operating mode, tow depth, or detection ranges back to the antisubmarine warfare reachback cell in the timely manner needed for it to be used to enhance environmental support. The Navy's current system, Undersea Warfare Decision Support System (USW-DSS), has been installed on many ships and provides communication between them at sea. One USW-DSS was installed at the antisubmarine warfare reachback cell between June and October 2014.

When the ambient noise data sensed on site can be delivered to the reachback cell, it can be used to refine noise levels used throughout the operating area to tailor more accurately any acoustic support products. While the noise can be measured very accurately at a point location, inferences can be made over a broader, but still relatively small, area depending on whether the measured noise is above, below, or near the expected values from databases. These new values, modified by comparison to the measured values, can be used for much better figure-of-merit calculation for sonar performance predictions. This will allow forward teams to formulate new and better recommendations for platform location and spacing, sensor setting, tow depths, and other tactical considerations. In turn, commanders can make better decisions faster and truly bring the "home field advantage to the away game."

Similar to ambient noise, reverberation levels are measured by sonar when operating in active mode and will be available to the reachback cell through USW-DSS. The short-term benefits in improving accuracy will be very similar to those from ambient noise improvements. Since scattering is typically less variable than ambient noise, however, these measurements will degrade in value over time less than ambient noise. The noise and reverberation data are automatically transmitted between USW-DSS machines to share the data amongst all ships in a composition. For this purpose, when the reachback cell joins a USW-DSS composition, it acts as a ship and receives the data as well.

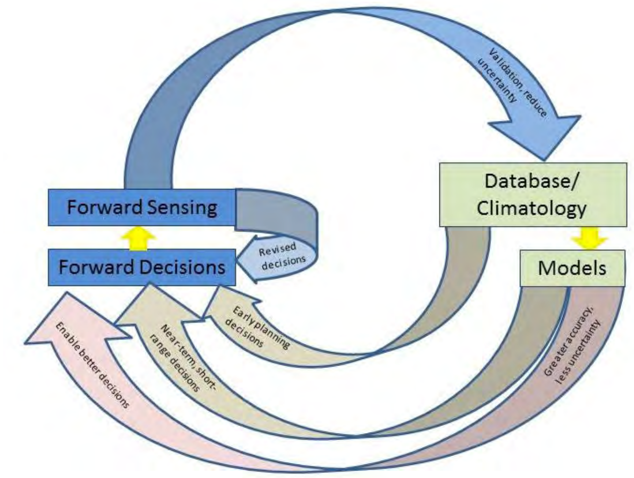
In addition to immediate improvement in real-time support, by completing the loop illustrated in the figure on the right, this data also will be processed for inclusion in the historical databases. Since the majority of the ambient noise data in the database was collected by buoys over long periods of time when no strike groups were operating in the area, just showing up with several ships greatly increases the ambient noise above the database values. Adding these observations to the database will provide a more complete distribution of noise values. This will ensure more accurate support through the "early planning decisions" and "near-term short range decisions" arrows show in the figure on page 17 for future operations.

Naval Special Warfare

Similar to the ambient noise and reverberation data scenario, the collection of littoral environmental parameters such as temperature, currents, and shallow water bathymetry in data-sparse or data-denied areas has never routinely been provided to a reachback cell in a rapid enough manner to influence ongoing special warfare operations. With operational timelines from mission planning to execution spanning as little as 72 hours, the utility of forward-collected observations has been minimized. In addition, these dynamic parameters are perishable, in that their relevance decreases over time. The opportunity for radical transformation within the decision making cycle, however, has greatly expanded with the advent of unmanned systems.

Technologically, the sensors on unmanned vehicles are robust, providing rapid, high-resolution observations over relatively large areas of particular relevance. By comparing these measurements with previously generated numerical forecasts, forward support teams can directly influence operational decisions relating to mission objectives, operating thresholds, alternate courses of action and optimal time lines. But, in addition, if these same data are provided back to the reachback location in a timely manner, the forcing and boundary conditions used to drive the numerical forecasts can be updated via data assimilation to provide more accurate predictions of these same environmental conditions. For example, an up-to-date surf zone bathymetric surface will greatly influence the location of rip currents and high breakers. This information, when coordinated with mission objectives will lead to greater operational success rates and safety.

Furthermore, if the forward teams operate similar to a USW-DSS composition, the on-scene mission plans can be



Complete Loop of Sensing and Decision Support

adjusted to have the numerical forecasts of winds, waves and currents influence the next round of data collection by placing the in-situ and unmanned tactical sensors in locations optimized for the types of decisions required. This culmination of the decision cycle would represent a dramatic improvement towards tasking sensors specific to ocean, atmosphere and physical battlespace decision support in the advanced sensing, modeling, feedback, environmental support loop represented by Figure 3.

An overarching goal of the NMOC's numerical atmospheric and ocean modeling effort is to provide high-resolution, probabilistic, fully coupled global and mesoscale air-sea-land-ice forecasts that will enable decision superiority across the Tasking-Collection-Processing-Exploitation-Dissemination and strategic planning cycles. For many denied area locations, this goal cannot be achieved without the ability to leverage both the forward and reachback component of NOOC's operational teams. The vision we describe allows for prediction of the battlespace environment over time scales relevant to both mission planning and execution while also optimizing the use of current and future manned and unmanned sensing technologies.

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USS *Bunker Hill* (CG 52) receives fuel from USS *Carl Vinson* (CVN 70) during a refueling at sea.

Photo by MCSA Dean M. Cates

TAKING WAVE PREDICTION TO NEW LEVELS: WAVEWATCH III

STRUCTURE CAN EMERGE FROM CHAOS WITH A LITTLE HELP.

By James D. Dykes, W. Erick Rogers, and Ruth H. Preller

To provide more effective meteorological and oceanographic support to the U.S. Navy, the Naval Research Laboratory (NRL) has transitioned state-of-the-art operational wave prediction technology to the Naval Oceanographic Office (NAVOCEANO) at Stennis Space Center, Mississippi, and to the Fleet Numerical Meteorology and Oceanography Center (FNMOC) at Monterey, California. Developed at the National Oceanic and Atmospheric Administration (NOAA), and used for civilian prediction at the National Weather Service, the WAVEWATCH III® numerical wave prediction model—featuring multigrid operability among other improvements—was tailored for the Navy's unique military demands, tested, evaluated for operational use in 2013, and declared operational in August 2014. The Navy system runs daily on high-performance machines at the Navy Department of Defense Supercomputing Resource Center.

Operational Support to the Navy

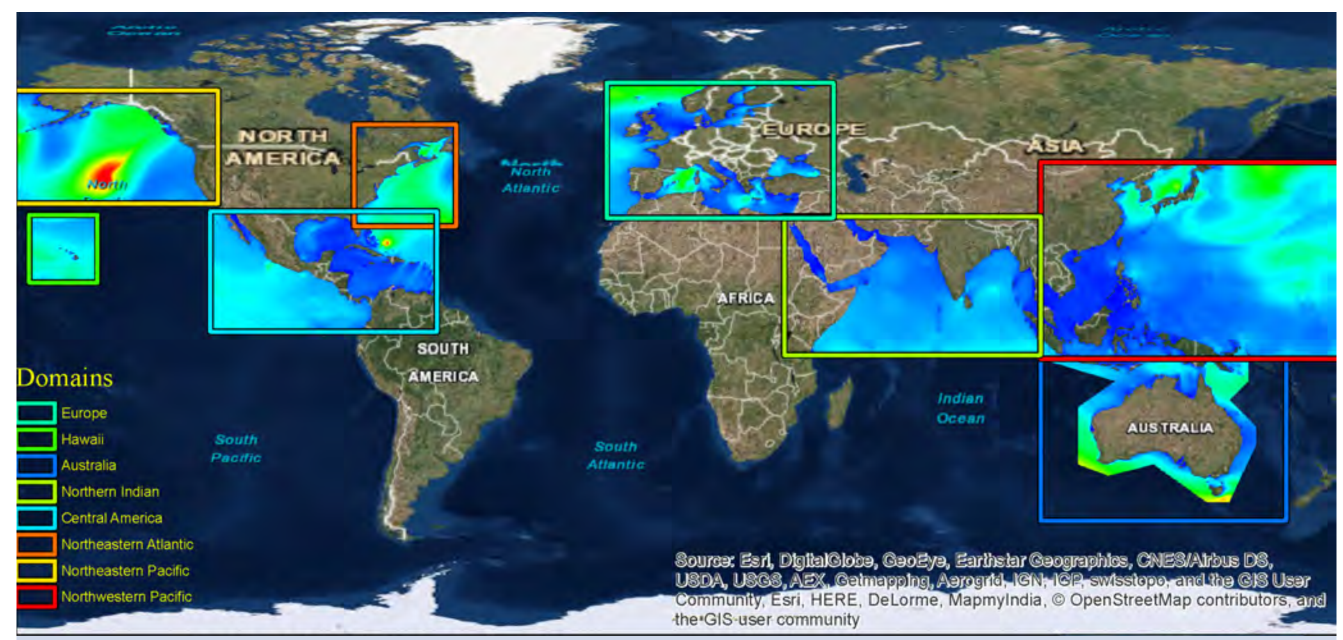
Large-scale wave models have a number of applications operationally, such as ship routing and high seas warnings. The most severe storms can generally be avoided by ships using meteorological forecasts, but a wave model improves prediction of wind waves by integrating effects of fetch, duration, and turning winds, and is essential to anticipate the swells emanating from these storms. Certain operations, such as ship-to-ship transfers of materiel, can be particularly sensitive to long swells. Forecasts of these conditions can be vital for operations planning. Knowledge of the general wave conditions helps trim costs in ship transit. Products from WAVEWATCH III, suited for these kinds of operations, include forecasts of wave height, direction and period (including swell), wave steepness scaled to platform size, and a crossing sea metric that defines regions with significant wave energy approaching from multiple directions.

Wave model forecast products used by the Navy do not only address large-scale requirements. Coastal, high-resolution wave and wave-affected predictions are essential to supporting numerous specialized Navy missions in the littorals, the areas for which forecast operations at NAVOCEANO are well suited. Directional wave spectral parameters from the global and regional domains are passed on to increasingly smaller domains along their boundaries for wave simulations performed by a variety of modeling systems. The smaller domain applications of these systems are used to resolve features such as surf and rip currents, conditions that affect special operations, amphibious assaults, and logistics over the shore. Changes in ocean optics due to re-suspended sediments caused by wave affects in the bottom boundary layer are especially important for diver visibility and mine countermeasures. Wave effects on harbors also are a concern for docked vessels in spite of the normally protective barriers.

Multigrid Approach

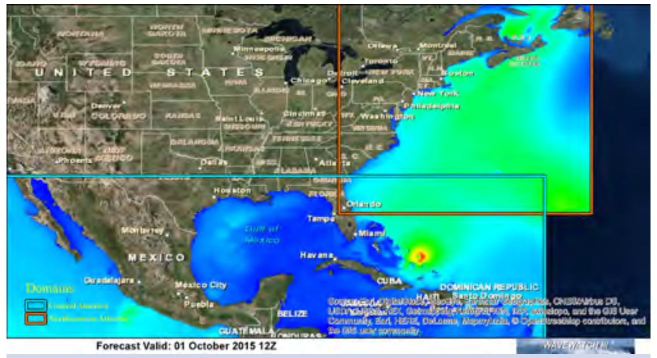
The Navy's current version of WAVEWATCH III features the capability of operating with gridded domains of multiple resolution simultaneously, ranging from 0.1-degree grid spacing in various coastal areas around the world to 0.5-degree spacing for the rest of the globe. Most of the higher resolution domains simply provide the complete coverage for the entire rectangular area. But, the domain around Australia is tailored for coverage near the coastline using a new capability that masks out offshore (open water) computational points, where the coarser global grid is used instead, saving computational cycles. All modeled waves are generated by surface winds that come from the synoptic scale meteorological models run at FNMOC. Many of the regional wave model domains receive winds from the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPSTM) models. Anywhere on the globe where COAMPSTM is not run, the model uses the winds from NAVGEM, the Navy's global spectral model for worldwide weather coverage.

Traditional modeling systems have been based on coarse grids covering large regions and smaller, finer gridded domains where more highly resolved results are required,



This represents the layout of the regional domains for an operational multigrid system. Each of the domains is filled with the significant wave height prediction valid for 1 October 2015.

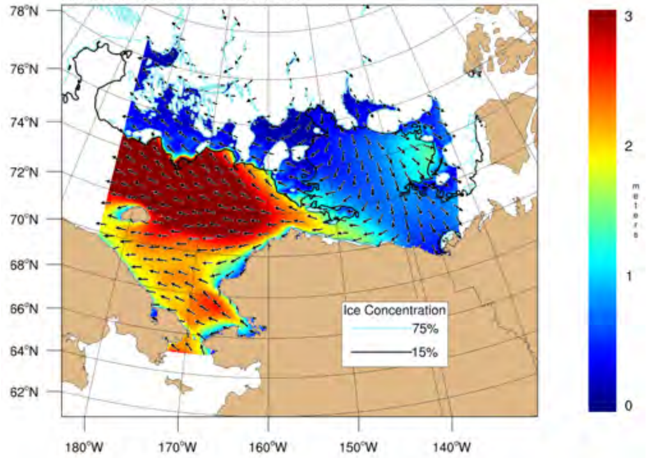
(e.g., near coasts). Wave spectra are typically passed one-way from the coarser model after it has completed—and at temporally coarse (e.g., three hours) increments—through the boundaries to nested higher resolution domains. The multigrid capability passes wave energy between domains in both directions at more frequent time intervals with simultaneous integration of all grids, which increases the potential for more accurate results. Thus, when winds generated by a mesoscale meteorological model such as COAMPS are applied to a higher resolution WAVEWATCH III domain, this innovative feature allows other domains to benefit from the potentially increased wave energy. An example of the effect of this feature is depicted in the figure below where waves generated by Hurricane Joaquin in one domain are allowed to propagate to another ultimately affecting the eastern sea board.



This shows wave heights on the waters surrounding Hurricane Joaquin. The colors, representing wave heights, show greater wave heights centered near the Bahamas.

Development Background

The WAVEWATCH model was originally developed at Delft University in the Netherlands. Its current form, WAVEWATCH III, was developed at NOAA's National Center for Environmental Prediction. The model is free and open source, with license restrictions. During the 2000s, the program evolved from code written by a single author into a community effort. A key enabler for the move toward a community-managed model has been a National Ocean Partnership Program for wave physics, funded primarily by the Office of Naval Research and NOAA. The latter provides the version-control infrastructure required for simultaneous development of the same code by numerous authors, including personnel from NOAA, Ifremer (France), the US Navy, the UK Met Office, Swinburne University (Australia), and others.



A sample product from WAVEWATCH III predicts wave conditions in the Arctic. For reference, the contours for ice concentration from the regional CICE ice model run at the Naval Research Laboratory are overlaid.

Using recent advancements in model physics, the latest model version can optionally represent certain source terms, including the effects of bottom friction, bottom scattering, sea ice, reflection from icebergs and steep shorelines, surf breaking, fluidized mud, and three-wave nonlinear interactions. In some cases, multiple options exist for the same physical process, allowing different theories, parameterizations, and numerical rigor. In addition to static bathymetry, the model optionally ingests several fields that may be non-stationary and non-uniform: surface currents, water levels, ice characteristics, 10-meter wind vectors, and air-sea temperature differences (to represent atmospheric stability). Unresolved islands and ice can be treated with a subgrid parameterization.

On the numerical side, WAVEWATCH III can perform computations on unstructured and irregularly structured grids. Propagation schemes using first-, second-, and third-order equations can be selected balancing accuracy against computational cost.

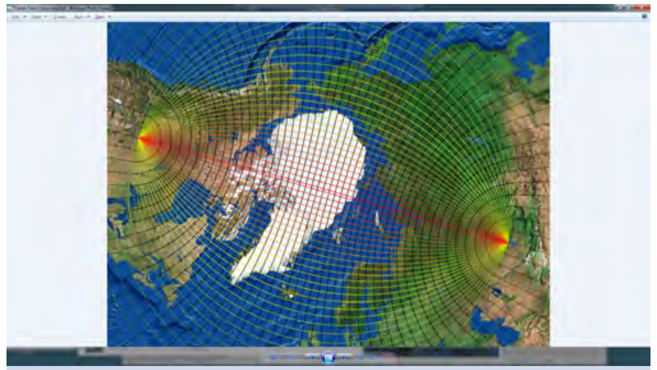
The timeliness of the operational runs of a wave model with such potentially complex configurations and diverse inputs is made possible with multiple options in parallel computing. On multiple processors, WAVEWATCH III computations can be distributed through message passing interface, with an innovative, two-phase domain decomposition of geographic and spectral grids during separate time steps for source-term calculation and geographic propagation, respectively.

Wave Predictions for the Arctic

The latest version of WAVEWATCH III has implemented new curvilinear gridded Arctic domains developed by NRL in response to a Navy requirement for wave prediction in the Arctic due to the recent decrease of ice cover in the summer and thus more open water. As participants in a Coast Guard operation in the Arctic, NRL demonstrated proof-of-concept operations providing real-time prediction products for atmosphere, ice and wave conditions. WAVEWATCH III was configured with curvilinear domains at 15 km and 5 km grid spacing using winds and ice from regional COAMPS and from the Navy's application of the Los Alamos Community Ice Code models, respectively. The propagation and dissipation of waves is affected by ice concentration. In this case, a threshold for ice concentration selected at 15 percent allows waves to propagate into the ice and then dissipate. At an ice concentration threshold of 75 percent, computational points are treated like land and no wave energy will penetrate. As USCGC *Healy* (WAGB 20) made its transit to the North Pole, predictions in ice concentrations became more critical to predict more precisely the sea state. The illustration above left depicts an example of a product of significant wave height and mean wave direction in the Chukchi and Beaufort Seas, including contours of ice concentration which was used as input into the wave model. These products were delivered twice daily on the NRL Monterey COAMPS on-scene web server.

Challenges for Fully Global Wave Prediction

This latest version of WAVEWATCH III lays the groundwork for the wave component of the Navy's Earth System Prediction Capability, which is a fully coupled atmosphere/ocean/ice/wave global prediction system. One of the challenges for efficient global coverage of wave simulations is resolving small features in the wave field that are caused by similarly small features in the forcing, e.g. ocean eddies and atmospheric mesoscale features, while not having to use an unreasonably small time-step, a common obstacle when solving numerical equations using a finite difference method. A spherical grid used for global coverage consists of meridians that converge toward the poles. If this type of domain were to extend too close to the poles, the meridians would narrow the grid spacing to a point that the propagation time steps would be impractically too small. A solution is a grid system where converging lines occur where no computations will occur such as over land, thus the idea of using a tri-pole grid. The figure below illustrates how two of the poles of the tri-pole grid are connected by a seam. Each of these poles is located in the continents of North America and Asia, while the third pole is the South Pole. An alternative approach is to use the multigrid capability with a combination of two high latitude curvilinear domains covering the Arctic and Antarctic and a ¼-degree resolution mid-latitude domain that extends to about 55 degrees N and 55 degrees S that, relative to the tripole grid, provides even more uniform grid spacing, and thus better efficiency.



This tripole grid layout for WAVEWATCH III for the i- and j-indices is decimated to about every 15th grid point for easier illustration. The j-indices are color enhanced to bring out the seam between two poles. Part of the grid in the Northern Hemisphere is shown.

These strategies and capabilities just described are possible thanks to the latest technology in state-of-the-art wave modeling using WAVEWATCH III and cutting-edge, high-performance computing. On-going efforts within the research community will continue to bring forward-thinking technologies to bear in support of naval operations with up-to-the-minute wave and wave-related predictions.

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USING ICE PREDICTIONS TO GUIDE SUBMARINES

NEW PROGRAMS ARE HELPING TO BETTER UNDERSTAND ICE IN THE ARCTIC – A REGION MORE IMPORTANT THAN EVER.

By Richard Allard, Pamela Posey, Dr. Ruth Preller, E. Joseph Metzger, and Julia Crout

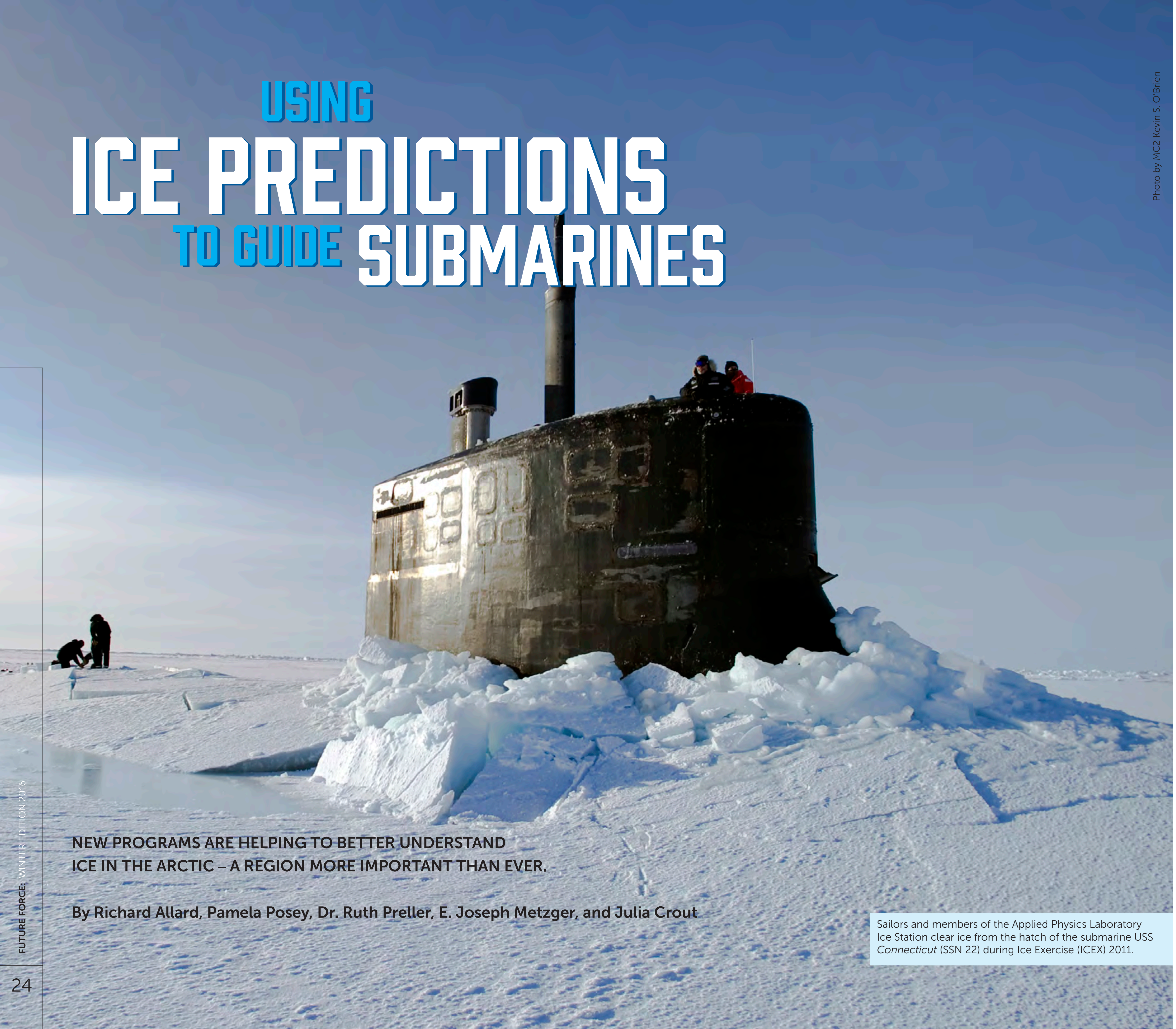


Photo by MC2 Kevin S. O'Brien

Sailors and members of the Applied Physics Laboratory Ice Station clear ice from the hatch of the submarine USS *Connecticut* (SSN 22) during Ice Exercise (ICEX) 2011.

Whether an Arctic mission requires the use of an icebreaker, Navy ships in open water, unmanned aerial or underwater vehicles, or even a submarine, knowledge of environmental conditions are of great importance to mission success and safety. For more than 50 years, submarines have conducted under-ice operations in the Arctic in support of interfleet transit, training, cooperative allied engagements, and other operations. A significant effort that occurs every two to three years is ICEX (Ice Exercise) which provides training opportunities as submarines transit the Arctic Ocean on their way between the Atlantic and Pacific Oceans. ICEX 2014, the most recent exercise, was brought to an unexpectedly early end. The ICEX began on 17 March and was scheduled to continue through 30 March. Large shifts in wind direction, however, created instabilities in the wind-driven ice floes of the Arctic Ocean, and these changes in the prevailing winds led to multiple fractures in the ice near the camp. These cracks prevented the use of several airfields used for transporting personnel and equipment to the ice camp. The rapidly changing conditions of the ice, along with extremely low temperatures and poor visibility, hampered operations.

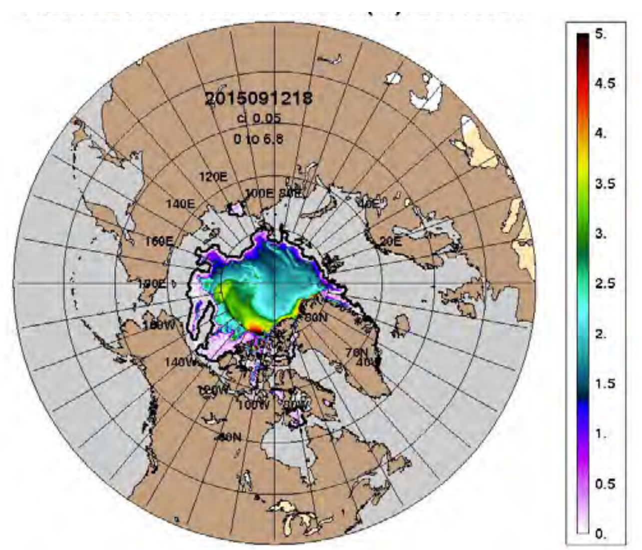
Submarines transiting under the Arctic ice use a guidance product developed by the National Ice Center called a FLAP (fractures, leads, and polynyas). A lead represents a crack or linear opening in the sea ice caused by divergent ocean current flows or wind effects. Leads are often transient and may quickly refreeze after the surface water encounters very cold air temperatures. A polynya is an area of open water surrounded by sea ice that often remains open because of warm upwelled water or warm coastal air. The FLAP "analysis" product is based on all available satellite imagery and provides a real-time indication of ice opening areas. The FLAP is provided to submarines prior to and during Arctic transits as a formatted text message that identifies navigation features in the ice over large areas. The message contains the latitude/longitude pairs delineating FLAPs, as well as remarks on the orientation and ice types. This is especially useful should the submarine need to surface for communications or in case of emergency and must find a location at which such operations may take place safely.

Scientists from the Oceanography Division of the Naval Research Laboratory developed and transitioned a new Arctic forecast system called the Arctic Cap Nowcast/Forecast System (ACNFS) in September 2013. The ACNFS consists of a coupled ice-ocean model that assimilates available real-time ocean and ice observations. The Global Ocean Forecast System (GOFS) 3.1, currently awaiting final operational approval, will replace ACNFS in the near future. Using similar components (ice, ocean, and data assimilation), GOFS 3.1 is a global coupled ice-ocean modeling system that gives the Navy the capability of forecasting ice conditions in both the northern and southern hemispheres. The ice component used for both systems is the Los Alamos Community Ice Code, a widely accepted model used in the ice community. ACNFS and GOFS 3.1 assimilate near-real-time observations of ocean temperature profile data (both in open water and under the ice), satellite-derived sea surface temperature and ice concentration, and satellite altimetry data. ACNFS and GOFS 3.1 are forced with atmospheric winds and heat fluxes from the Navy Global Environmental Model. Both systems have high horizontal resolution (3.5 kilometers at the North Pole) and generate seven-day forecasts of ice thickness, ice concentration, ice drift, ocean surface and subsurface temperature, salinity, ocean current, and 40 additional two-dimensional products. Both systems are run daily at the Naval Oceanographic Office with products automatically pushed to the National Ice Center for guidance in developing daily/weekly ice charts.

Confronting an Icy Domain

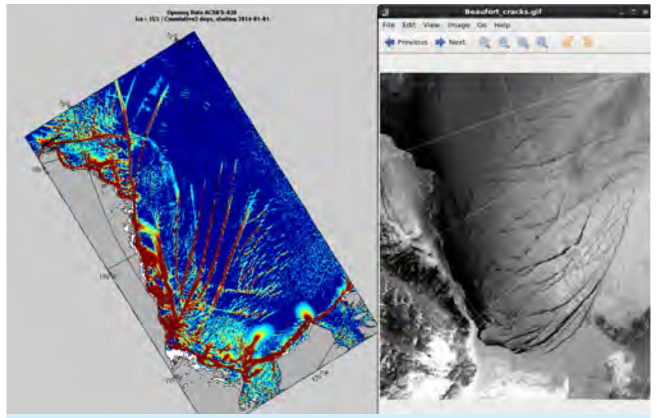
Military operations carried out in the harsh Arctic environment can be very challenging. Winter air temperatures can plummet to -40 degrees Fahrenheit or colder, high winds and breaking waves occur, and a continuously changing ice cover can make previously open water regions impassable. In recent years the Arctic has experienced numerous changes. These include an overall thinner ice cover, an increase in open water in the summer, and larger waves. The National Snow and Ice Data Center, which monitors Arctic sea ice from satellite observations, has observed a substantial reduction in summer sea ice extent when compared to the 30-year average (1981-2010) and have recently stated that the summer sea ice extent in 2015 was the fourth lowest recorded in the satellite record (behind 2012, 2007 and 2011). In addition, the nine lowest summer ice extents in the satellite era have all occurred in the last nine years. Satellite data and drifting buoy information can also be used to determine the "age" of the ice cover. The age of the sea ice serves as an indicator of its physical properties including surface roughness, melt pond coverage, and thickness. Older ice tends to be thicker than younger ice. These observations indicate that although there are year to year fluctuations in the amount of old versus new ice, the amount of old ice has been greatly reduced since the 1980's when the oldest ice made up a larger fraction of the pack. These recent changes in the Arctic environment make the prediction of sea ice conditions based on climatology, mean conditions, or even the previous year's conditions impractical.

Prior to the operational acceptance of these forecast systems, the National Ice Center actively takes part in performing an evaluation of these modeling systems, with particular emphasis on evaluating the predictive skill of the ice products of the models. One of those products is the lead opening rate, which provides information on areas where new leads may form or grow based on divergence of the ice pack, typically produced by wind force acting on the ice. Although not part of the initial validation process, the National Ice Center asked the Naval Research Laboratory's Oceanography Division to validate ACNFS and GOFS 3.1 by evaluating the systems' relative skill at predicting the areas where FLAPs would develop.



An example product from the Arctic Cap Nowcast/Forecast System (ACNFS). Ice thickness is in meters for 11 September 2015. Thickness ranges from zero to five meters as shown in color bar. Gray areas represent open water. The thick black line is an independent ice edge analysis from the National Ice Center.

The ACNFS and GOFS 3.1 capabilities were then extended to capture and predict the opening of sea ice areas (fractures/leads) and polynyas by calculating areas of ice convergence and divergence, ice opening rates, ice ridging, and ice shear. The ACNFS and GOFS 3.1 opening rate is an instantaneous value representing how fast an opening event is occurring. It does not, however, reflect ice opening from previous days. An innovative technique—using weighted model-derived opening rates from the three prior days to the analysis time as well as calculated convergence over that time—generated the validated ACNFS and GOFS 3.1 FLAP analysis product. A key advantage is that the ACNFS and GOFS 3.1-derived FLAP analysis can provide valuable information in cloud covered areas or other areas where satellite imagery may not be available.



ACNFS opening rate in percentage/day (left) and MODIS imagery (right) valid for 1 January 2014 for the Beaufort Sea area. Black areas on imagery indicate leads and open water.

Knowledge of where openings are currently present is most important for daily ship and submarine navigation; knowledge of the future timing and location of significant fracturing is most important for operations planning. As such, the National Ice Center also expressed an interest in the ability to provide five-to-seven day FLAP forecasts for mission planning. To meet this need, the Naval Research Laboratory used their ACNFS and GOFS 3.1 forecast systems to provide a new capability—a seven-day forecast product of opening rates that represent areas of FLAPs in the Arctic. This capability has been developed, demonstrated, validated, and transitioned to the Naval Oceanographic Office and is provided daily to the National Ice Center. These forecasts show substantial improvement over persistence and can be used as guidance to support planning and decision making for Arctic missions.

Both ACNFS and GOFS 3.1 opening rate products were validated for an 11-month period of FLAP messages from January through November 2012 provided by the National Ice Center. The FLAP messages (around 80 classified text files) provided reference data to validate the ACNFS and GOFS 3.1 analysis and forecasted products. For each message, the number of fractures and polynyas along with the orientation were noted. Comparison metrics were completed for each message fracture noting the model agreement category as strong match, partially covered, location off, subset of field, or no match. A combined "hit/near hit" was achieved at a rate of 88 percent for all the model test cases evaluated during the 11-month period. Locating the "near hit" areas is just as valuable as a "hit" to a submarine, which will then know the general area to use their upward-looking sonar to locate a safe place to surface. During this evaluation, the modeled products were compared against satellite imagery, such as the Moderate-resolution Imaging Spectroradiometer and NASA's Visible Infrared Imagery Radiometer Suite.

In August 2015, the National Ice Center determined that the ACNFS and GOFS 3.1 products were useful to ice analysts as a resource to develop special support and FLAP products for their customers.

The ice-ocean coupled models that form the basis of the forecast systems described in this article will soon become the oceanographic component of the Navy's Earth System Prediction Capability (ESPC). ESPC will be a global model that includes coupled ice-ocean-wave-atmosphere models that assimilate all available observations. The coupled system should provide better and longer forecasts for the globe resulting in even better forecasts of Arctic environmental conditions that impact Navy missions. This program funded by the Oceanographer of the Navy and managed by the Office of Naval Research is part of the larger national ESPC effort.

About the authors:

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Dr. Preller is the Superintendent of the Oceanography Division and previously led the polar research team at the Naval Research Laboratory.

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Photo courtesy of Naval Air Systems Command

Field experiments were conducted on the hybrid lidar-radar system in the Chesapeake Bay with the bistatic imaging system aboard R/V *Rachel Carson*.

CARRYING RADAR SIGNALS WITH LIGHT

A NEW LIDAR-RADAR HYBRID CAN HELP PLATFORMS USE RADAR DETECTION UNDERWATER.

By Dr. Linda Mullen and Dr. Brandon Cochenour

One of the components needed to achieve and maintain assured access to the maritime battlespace is sensor superiority. Undersea threats must be detected, classified, and identified with high accuracy and low false alarm rates so that threats can be targeted. The detection process involves observing a feature that is uniquely relative to the surrounding environment and is consistent with the objects being sought (e.g., a round or large cylindrical object). The next step, classification, happens when operators categorize objects within a group of similar objects (e.g., a mine-like object or a submarine). Identification of the threat requires that object features are resolved accurately and quickly to determine with certainty what the objects are (e.g., a specific type of mine or a particular class of submarine) so the information can be communicated to those who can eradicate the threat.

Radio frequencies, while ubiquitous on land, experience high attenuation in water and therefore cannot be used for wireless communications or detection, classification, or identification undersea. It is for this reason that acoustic-based sensors and modems have historically been and continue to be used for these tasks. Acoustic technologies, however, lack the resolution typically needed for the identification step and have insufficient bandwidth for high-speed wireless communications. Acoustic frequencies also cannot penetrate the air-sea interface.

Lidar Sensors in Water

Lidar, or light detection and ranging, is the laser-based equivalent of radar and sonar. The highly directional properties of the laser output provide lidar systems with the resolution to accomplish the identification task. Lasers also have an inherently high bandwidth that enables them to be used for high-speed wireless communications. Furthermore, the fact that we can see objects in the water from both above and below the air-sea interface provides evidence that light can propagate through the water surface and within the water column. We know from viewing underwater photography, however, that light does not propagate through water the same way as it does in air. As light travels through water, it is absorbed and scattered by water constituents. The higher absorption of certain wavelengths or colors of light leads to the blue-green hue of underwater imagery, while scattering of light in water causes the haze or blurring of details.

Despite the challenges of light propagation in water, lidar sensors can adapt to the underwater environment. Lasers operating in the blue-green portion of the spectrum can be selected to minimize absorption and maximize transmission in water. The scattering problem is more difficult to overcome as light can scatter back to the receiver without ever reaching the object of interest (backscatter) and scatter multiple times at small angles on its path to and from the area of illumination (forward scatter). Backscatter tends to decrease the overall contrast of the collected imagery, while the collection of forward-scattered light causes image blurring and loss of spatial resolution or sharpness of the image. Similar to driving on a foggy night, turning up the laser power (like turning on the high beams) does not improve visibility in murky water since more light will only scatter back from particles in the water. Increasing the separation between the laser and receiver can help suppress backscatter, just as the fog lights that are further away from our line of sight on a car can enhance visibility in fog. The highly directional properties of laser light can be leveraged to reduce scattered light by limiting the receiver aperture and acceptance angle to view only the laser-illuminated spot some distance away. Furthermore, sensors using a pulsed laser source can reduce backscatter by timing the receiver to open at a time corresponding to the round-trip time to the object of interest.

Hybrid Lidar-Radar

Researchers at the Naval Air Warfare Center Aircraft Division (NAWCAD) in Patuxent River, Maryland, are investigating an alternate approach to enhance optical imaging in water. This hybrid technique (described in patent "Modulator Lidar System," No. 5,822,047, 13 October 1998) uses a laser to transport a radar signal through the water. By encoding the laser pulse with a radar signal, the receiver can "lock on" to a signal reflection from an object and distinguish it from light scattered randomly from the environment, analogous to how our eye locks onto the strobe light on a school bus on dark, foggy mornings. Using a laser to carry a radar signal through the water provides a way to use the sophisticated radar modulation, demodulation, and signal processing techniques developed for above-water object detection and identification for similar applications in water, an environment where radar signals cannot be used directly because of their high absorption. The encoded waveform also can be altered to include information to be transmitted to another location, which would enable the sensor to be used for both object detection/imaging and wireless optical communications.

The group at NAWCAD has leveraged Office of Naval Research and in-house funding to focus its research in three main areas: environmental characterization (measuring the water optical properties using in-situ instruments and use data collected by the laser system to enable "through the sensor" environmental measurements); performance prediction modeling (using the information collected in the first area as inputs to theoretical models developed both in-house and through collaborations with academia and industry to predict the effectiveness of the approach for different applications and system parameters); and experimental measurements (designing and developing breadboard prototypes to validate model predictions and demonstrate system performance in a controlled laboratory environment). Comparisons between model predictions and experimental measurements are used to provide feedback to the environmental characterization task to identify whether new and/or improved measurements are required to improve the correlation between theory and experiment. Similarly, there is feedback between modeling and experiments to determine the accuracy of the underlying theory and/or to explain the physics involved with new or unanticipated results.

Characterizing the Underwater Environment

Current research has focused on improving measurement through the inherent optical properties of water: scattering and absorption. The NAWCAD group works closely with academia, industry, and other government laboratories to enhance the accuracy of the data provided by state-of-the-art, in-situ instruments. Alternatively, the group has developed custom lidar systems that can extract water optical properties from the detected signal. This environmental characterization uses variations in the system parameters (e.g., receiver acceptance angle, laser/receiver polarization) to enhance the sensitivity of the sensor to specific water optical properties. For hybrid lidar-radar applications, the group is particularly interested in how the water optical properties influence the propagation of radar-encoded optical signals. Measurements using modulated laser beams have shown that the encoded radar signal is sensitive to small changes in the scattering phase function, which describes the angular distribution of light scattering in water and has traditionally been a very difficult parameter to measure in-situ.

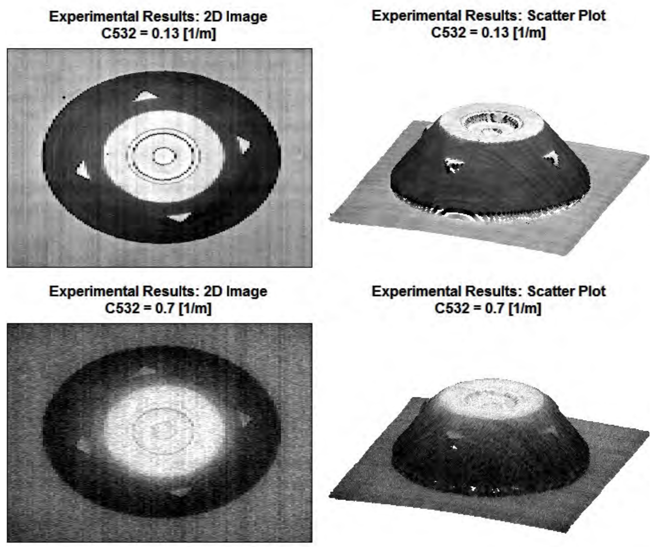
Predicting the Results

The goal of this research involving theoretical model development is to create a time-dependent model that can predict the effect of water optical properties (absorption, scattering), system parameters (transmitter beam divergence, receiver aperture and acceptance angle, transmitter/receiver separation), and object characteristics (size, shape, reflectivity, depth) on the propagation of an impulse of light through water. Once this optical impulse response is computed, it can be combined with any type of radar or communications waveform and processed accordingly. Monte Carlo methods (i.e., random sampling) fall into the numerical category of underwater models as they trace the path of individual photons through a medium according to the inherent optical properties of absorption and scattering. While computationally intensive, the Monte Carlo method provides an exact solution since it tracks individual photon paths. Numerical models may require significant processing time, however, particularly in turbid environments, to simulate enough photons to be statistically accurate.

The other category of underwater propagation models uses analytical methods, which are based on the solution of the radiative transfer equation, a complicated integro-differential equation of several variables in space and time. Certain approximations are typically made to reduce the problem to provide a manageable solution. Current research efforts are focused on studying how these approximations affect the accuracy of predicting the effect of the water on the radar-encoded signal.

Cutting-Edge Hardware

The main challenge in performing experimental measurements with radar-encoded optical signals in water is the hardware required to generate and detect these high-speed signals. On the transmitter side, a high-power, blue-green laser source with high-speed, efficient modulation is required. A wide-bandwidth, high-sensitivity optical detector is needed on the receiver end to recover the radar-encoded signal. Fortunately, the group has leveraged the Small Business Innovation Research (SBIR) program to fund industry collaborators in developing the necessary hardware for breadboard prototypes. Both SA Photonics, Inc. (Los Gatos, California), and Fibertek, Inc. (Herndon, Virginia), delivered blue-green, modulated pulse laser sources



These images were collected using a hybrid lidar-radar prototype in a controlled laboratory water tank environment. Two-dimensional (left) and three-dimensional (right) images were processed for a manta mine-like target in both clean (top) and murky (bottom) water environments.

through a SBIR Phase II program. These sources produce optical pulses whose radar modulation can be easily controlled via software commands, which provides a way to test the effect of different radar waveforms on system performance.

Through the same SBIR topic, AdvR, Inc. (Bozeman, Montana), is developing a device that can impose the radar modulation on a commercially available pulsed laser. This approach offers an alternative modulated pulse source that does not require the development of a complete custom laser. AdvR also has produced a continuous-wave, modulated blue-green source that has been used for both imaging and communications applications. These hardware developments, combined with the advancements in high-speed digitizers and field programmable gate arrays, has made it possible to generate, detect, and process sophisticated radar modulation waveforms. The water tank at NAWCAD is 25 feet in diameter and 10 feet deep, and is outfitted with windows that provide a convenient way to transmit and receive light through water from a benign, dry environment. Various targets of interest can be easily mounted from an overhead bridge that spans the length of the tank, and the absorption and scattering properties of real-world water types can be reproduced in the lab through the addition of artificial scattering and absorbing agents and monitoring by in-situ optical instruments.

Putting It All Together

Recent imaging experiments have focused on the use of wideband “chirp” radar modulation schemes and subsequent pulse compression processing at the receiver. The technique uses a modulation waveform whose frequency is swept—or chirped—as a function of time. By transmitting a unique modulation signature on the optical signal, a receiver that knows the transmitted waveform can use “pattern-matching” techniques to look for its own unique signature being echoed back from targets. This process of pattern matching a chirp waveform is referred to as “pulse compression,” where a longer pulse encoded with a wide-bandwidth waveform is compressed into a short pulse at the receiver. Thus, the chirp modulation and subsequent matched filter processing provides a way to obtain a high time (or range) resolution measurement by using a wider transmitted pulse. Furthermore, when applied to the underwater sensing, the frequency content can be tuned to optimize the rejection of unwanted scattered light, which enables the system to adapt to different water environments.

Recent experiments were conducted in the water tank at Patuxent River to test the chirp modulation/pulse compression technique against realistic targets and in different underwater environments. A plastic manta mine-like target was suspended in the water column and illuminated with the system. Two- and three-dimensional images were created in both clean water (no scattering agents added) and in murky, harbor-like conditions. The results show that the technique has the potential to provide the high-resolution imagery needed for object identification in challenging underwater environments.

Future Trends

The Navy is trending toward using compact, unmanned, autonomous platforms to improve access to strategic areas of interest without the risk involved with manned platforms. The size, weight, and power of current laser-based sensors, however, are not compatible with small, unmanned, and autonomous underwater vehicles because these existing systems incorporate transmitter and receiver hardware on the same platform. To improve the compatibility of laser-based sensors with unmanned aerial and subsea vehicles, the NAWCAD team developed a technique (described in patent “Extended Range Optical Imaging System for use in Turbid Media,” No. 8,373,862, 12 February 2013) where the transmitter and receiver are located on separate platforms. While unique to laser-based sensors, this bistatic geometry has been used extensively in both sonar and radar sensors. For a laser-based sensor operating in degraded visual environments such as murky water, the bistatic configuration enables the transmitter to optimize its distance from the object of interest so that the amount of light scattered on the path to the scene is minimized. The laser is encoded with information concerning the scan, such as scan rate or scan angles, and the receiver decodes and uses this information to reconstruct the underwater image in real time, expediting decision making by eliminating the need to wait for the illuminator to return to the operator before data can be downloaded and analyzed.

The strength of this approach is that the transmitter and receiver are entirely autonomous and are linked only by a wireless communication signal that is carried by the light scattered from the object and from the environment. Furthermore, this approach supports distributed sensing since a swarm of laser illuminators can be deployed to survey an area of interest. Mission time is reduced as a single receiver can immediately collect and process information from many illuminators. The multistatic architecture also offers multifunctionality since both high-resolution imaging and high-speed laser communications are available from the same sensor suite.

The hybrid lidar-radar approach enables the use of well-established radar modulation, demodulation, and signal processing techniques for optical sensing and communicating in a wide range of underwater environments. This hybrid approach provides a solution for generating high-quality imagery so that underwater threats can be identified, and the same hardware can be used to communicate the threats to those in danger. By using the same hardware for sensing and communicating, unique system configurations are possible that make laser-based sensors more compatible with small underwater platforms. Ongoing research in environmental characterization, theoretical modeling, and experimental validation will help close the loop between experiment and theory so that the performance of these hybrid systems can be accurately predicted for scenarios not easily represented in a controlled laboratory environment. This will be an important step in developing the next generation of sensors to achieve and maintain assured access to the maritime battlespace.

About the authors:

Drs. Mullen and **Cochenour** are researchers at the Naval Air Warfare Center Aircraft Division.

 By Patric Petrie

THE MARITIME INTERDICTION OPERATION UNMANNED GROUND VEHICLE

BOARDING TEAMS NOW HAVE A LITTLE FRIEND TO HELP SEARCH SHIPS AT SEA.

Every year the U.S. Navy performs thousands of maritime interdiction operations worldwide to enforce embargoes, intercept contrabands, prevent drug and human smuggling, and fight piracy. These operations are usually conducted by visit, board, search, and seizure (VBSS) teams using rigid-hull inflatable boats (RHIBs).

Most boarding operations are "compliant" (i.e., the target ship complies with the Navy's order to stop, and lowers a ladder for the boarding team), but a fair number are noncompliant, where orders are ignored. In this case, the RHIB has to match the speed of the suspect ship, and team members must board using rope ladders with grappling hooks. Once aboard, the VBSS team quickly secures the deck and the pilot house, and then begins a sweep of the rest of the ship. One of the most dangerous operations during this phase is the descent into the hull of the ship. The concept of operations may call for the dropping of flash-bang grenades down a ladder well, or a person hanging upside-down providing cover fire for others to rush down.

To assist VBSS teams in these operations, Space and Naval Warfare Systems Center (SSC) Pacific has developed a Maritime Interdiction Operation Unmanned Ground Vehicle. It is a small mobile robot with video camera that can be thrown onto the deck of a ship from a RHIB for an advance look, down a hatch once the deck has been secured, or into individual ship compartments during clearing operations. It also has other tactical features such as an optical dazzler to stun potential opponents in a dark compartment before the team enters, the ability to swim on the water surface of flooded compartments or bilges, and the ability for one operator to control two robots, with one providing a rear-guard function (with motion detection) as the team moves ahead.

Working with VBSS teams and trainers, SSC Pacific's unmanned systems group provided the overall concept development, key performance parameters, project management, and testing of prototypes. The actual design of the robots was performed under contract by Macro USA.

User tests were first conducted with VBSS trainers to determine the exact robotic-support requirements for operations, leading to the development of a set of key performance parameters for a robot that would meet their needs. Using these specifications, we competitively selected a developer, Macro USA, to build two prototype systems, each consisting of one controller and two robots (called Stingray). The prototypes were then demonstrated or loaned to Navy, Coast Guard, and Marine VBSS teams to collect feedback for a potential second-generation design.

The initial predevelopment discussions and user tests to determine the key performance parameters of the robot were with members of the Navy's Maritime Security Squadron 3 and Afloat Training Group San Diego. These tests, conducted using robotic tools available at that time, revealed some surprising user requirements. Aside from establishing the ideal size and weight for a throwable robot, the tests revealed unique characteristics required for maritime tactical environments – such as appropriate wheel size to navigate ship deck gratings, no external antennas or tails that could get caught in a cluttered ship environment, positive buoyancy and the ability to traverse water surfaces, and elimination of operator-control-unit neck straps (to prevent their use in choking the operator during hand-to-hand combat).

The resulting prototype units exhibit these and other features that make them ideal tools for tactical use in the maritime environment: a drop rating of five meters onto a steel deck; the ability to climb over objects commonly found on ship decks, such as cables and chains; a waterproof capability up to one-meter depth for 30 minutes; high-traction wheels that can maintain position on a slippery deck in rough seas; steerable visible-light and near-infrared LEDs; visible strobe LEDs that can be activated to aid in locating the robot in darkness; a high-intensity LED dazzler to disorient opponents; rope and pole attachments to position the robots in hard-to-reach places or to use the robot as an extended hand-held sensor; and the ability for one controller to operate two robots, with the robot not being under active control having a motion-detection capability to act as a rear guard for the team.

Following the design and production of the prototypes by Macro USA, evaluations of the units were conducted by the III Marine Expeditionary Force VBSS team in Okinawa, Japan; the Coast Guard component of Joint Inter-Agency Task Force South at Opa Locka, Florida; and the Navy VBSS teams at Naval Station Mayport, Florida.

Feedback from user tests of the prototypes has been very positive. The warfighters have communicated a strong desire to have this system in their bag of tools. The Marine Corps even went one step further, expressing an interest in a variant of the system with more aggressive wheels, to be used on non-VBSS tactical missions.

The field of robotics is playing a more prominent role in warfare every day, with unmanned aerial vehicles providing overhead imagery or long-distance strike capabilities, unmanned ground vehicles defusing improvised explosive ordnance, and unmanned underwater vehicles providing environmental undersea maps.

No previous robotic capability, however, has been made available to support the dangerous naval mission of boarding potentially hostile vessels. This project aims to rectify that oversight.

The system will reduce risks to VBSS teams, providing a look-ahead capability before they enter dangerous situations, such as poking their heads up above the deck railing as they attempt to board a ship, descending down ladders into the interior of a boarded vessel, or clearing compartments where hostile opponents may be hiding. It also will reduce time and costs for searching for contraband hidden in bilges and flooded compartments.

The Maritime Interdiction Operation Unmanned Ground Vehicle is an asset built to support Navy, Marine Corps, and Coast Guard missions and assists warfighters in all critical phases of interdiction operations. Currently, SSC Pacific is looking for support to execute the necessary modifications and enhancements identified through field tests of the prototype units, to better position the system for fielding.

About the author:

Patric Petrie is the lead staff writer for Space and Naval Warfare Systems Center Pacific.

A LOOK AHEAD

BUILDING THE FUTURE NAVAL S&T WORKFORCE

▶▶ By Dr. Terry Allard

The next issue of *Future Force* focuses on how the Department of the Navy is recruiting and developing the scientists and engineers (S&Es) and the critical "business of science" people, services, and processes required to invent the future of the Navy and Marine Corps.

The rate of technological change is ever increasing. The federal government is no longer the primary driver of new defense technologies. We have to keep an ever closer watch on global science and technology (S&T) developments that now are often driven by the commercial marketplace. Our friends and our adversaries are contributing breakthroughs in the public literature and behind closed doors. We must establish global partnerships and collaborations with the worldwide S&T community. We need to identify and cultivate new ways of getting the job done efficiently and effectively, increasing the exchange of people and ideas and keeping our technical edge as we compete in a complex technological landscape.

An important challenge is communicating the Navy and Marine Corps S&T mission and opportunities to diverse communities that comprise the naval S&T workforce of the future at all age levels. The Office of Naval Research's research investments at universities across the nation are educating graduate students, postdoctoral scholars, and junior faculty about the national priorities of the Department of Defense. The naval S&T community must build an effective bridge to industry, government, and academia to communicate the excitement of discovery and invention that is critical to future naval capabilities and missions.

A wide variety of human resource mechanisms will help the Naval Research and Development Establishment (NRD&E) identify, recruit, and retain a world-class S&E workforce that brings 21st-century skills and perspectives to bear on emerging naval challenges. Science, technology, engineering, and math (STEM) programs across the NRD&E provide a path for promising young students and professionals to enter the workforce and partner with industry, government, and universities across the country. We would like to leverage lessons learned from the Navy's Sailor 2025 manpower, personnel and training efforts to the civilian S&E workforce.

Topics for the Spring 2016 *Future Force* will address a wide range of issues such as STEM education, hiring and career development issues, diversity opportunities, and interactions between industry, government and academia. We will be reporting on inputs from across the NRD&E research laboratories and program offices wherever there is opportunity for innovation and new naval capabilities. The future of the Navy and Marine Corps on the world stage will be in the hands of the next generation of scientists and engineers and hinges upon the critical people and processes that enable the "business of science" as we move forward.

Dr. Allard is the director of the Warfighter Performance Science and Technology department at the Office of Naval Research.

Photo by John F. Williams

Naomi Delgado Cruz (left), a mechanical engineering senior at the Polytechnic University of Puerto Rico, and physics major Derick Buckles, from Morgan State University in Baltimore, Maryland, participate in a 10-week summer research program at the Naval Research Laboratory for students from historical black colleges and universities and minority institutions.

EOD2 Matthew Krom assigned to Commander, Task Group 56.1 enters the Arabian Gulf to locate a training mine during a quarterly Squadron Exercise (Squadex). Squadex is a mine countermeasures exercise designed to assess the abilities of U.S. Navy explosive ordnance disposal units and reaffirm their proficiency with the units' latest equipment. CTG 56.1 conducts mine countermeasure, explosive ordnance disposal, salvage-diving, and force protection operations throughout the U.S. 5th Fleet area of operations.
Photo by MC2 Torrey W. Lee

FUTURE FORCE is a professional magazine of the naval science and technology community published quarterly by the Office of Naval Research.

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