2016 NRL REVIEW

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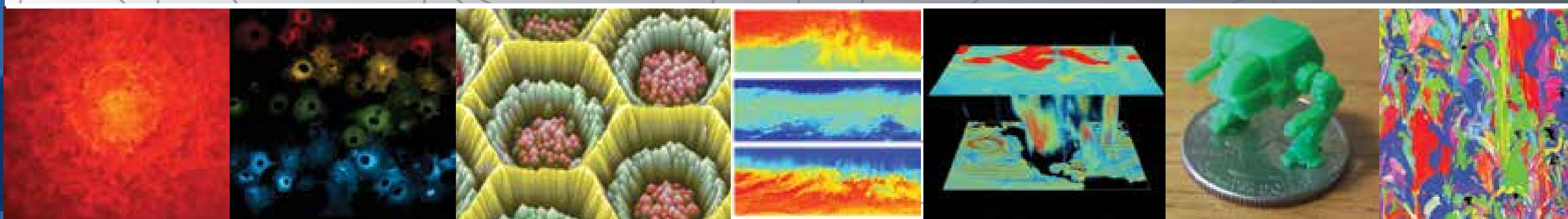
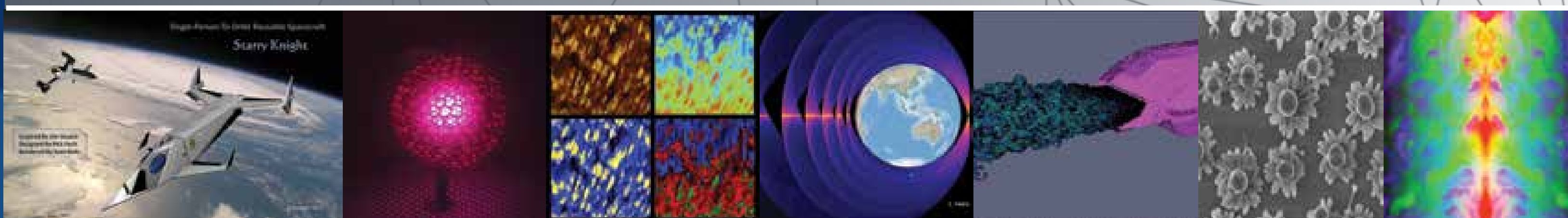
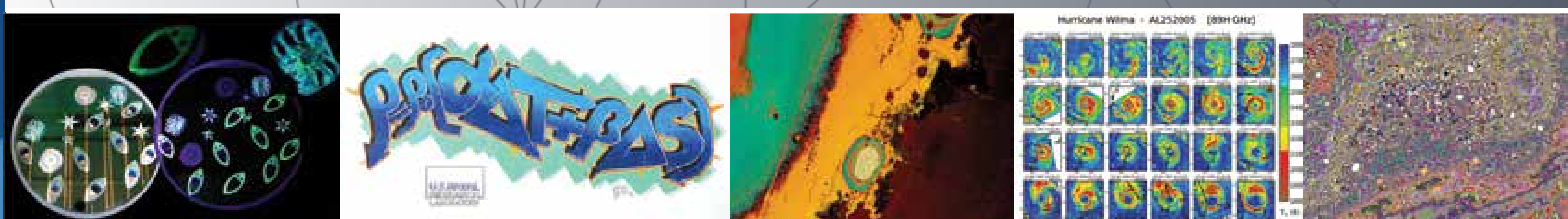


We are explorers



We are protectors



We are futurists

U.S. NAVAL RESEARCH LABORATORY

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We provide the advanced scientific capabilities required to bolster our country's position of global naval leadership. Here, in an environment where the nation's best scientists and engineers are inspired to pursue their passion, everyone is focused on research that yields immediate and long-range applications in the defense of the United States.

U.S. NAVAL RESEARCH LABORATORY

ON THE COVER: The winners of the 2016 NRL Science As Art contest held in August/September 2016.

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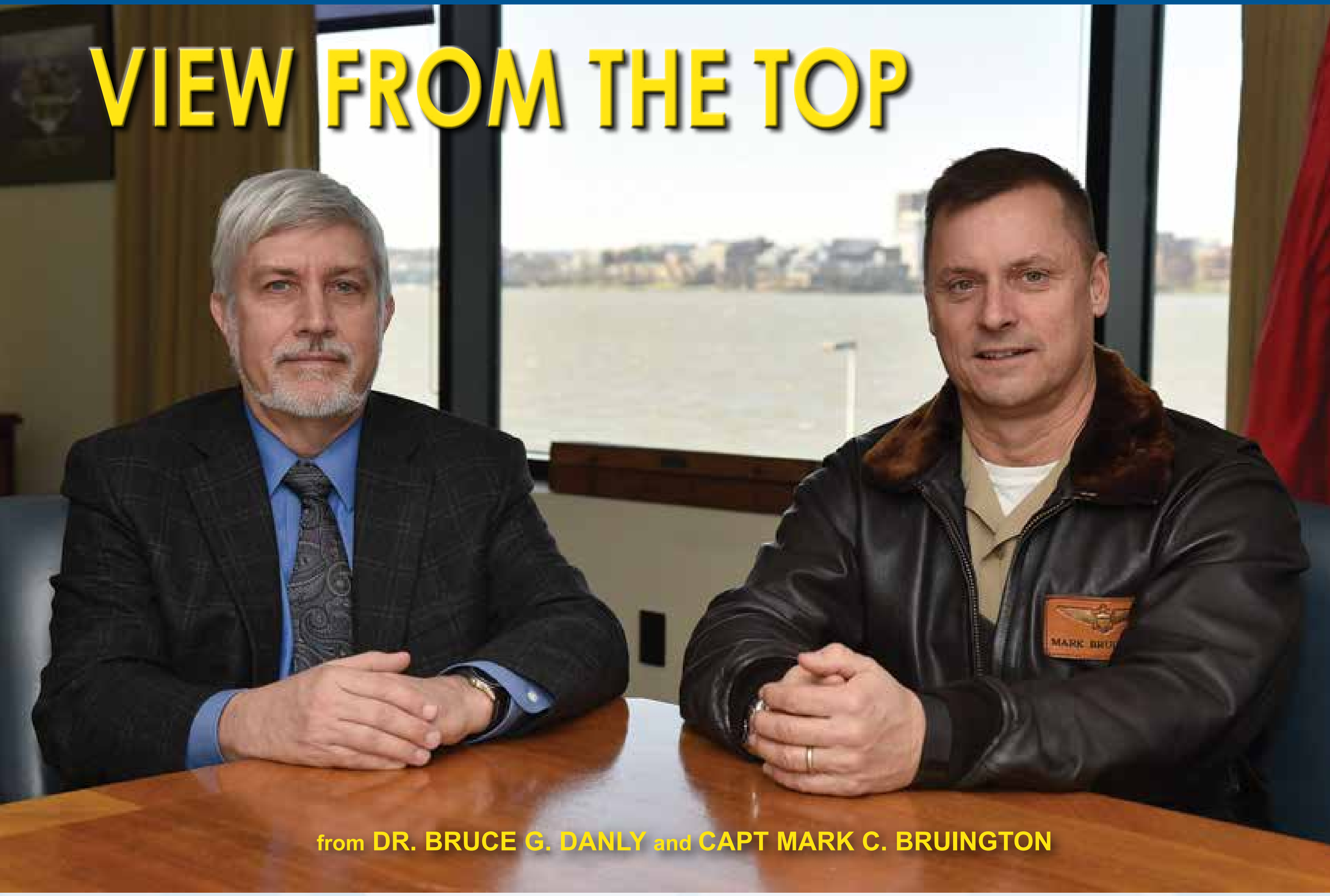
VIEW FROM THE TOP



from DR. BRUCE G. DANLY and CAPT MARK C. BRUINGTON

The U.S. Naval Research Laboratory enjoyed another exceptional year of accomplishments in 2016. Our researchers, engineers and support team continue to provide cutting-edge science and technological improvements to the Navy/Marine Corps, while receiving well-deserved recognition for their significant work and accomplishments.

In addition to the many accomplishments you will read about in this year's *Review*, we are honored to welcome our new Chief of Naval Research Rear Admiral David Hahn. CNR took the helm of the Naval Research Enterprise in late 2016, emphasizing his three-part leadership philosophy: mission accomplishment, teamwork, and personal growth and development, challenging all NRL employees to consider how our efforts support ONR's mission to plan, foster and encourage scientific research in support of future naval power.

We also announced Dr. Bruce Danly as the new NRL Director of Research in December 2016. Dr. Danly has served at NRL since 1995, most recently as the Radar Division superintendent.

We are extremely proud of the countless research projects and recognition highlighted throughout this *Review*. Some of those include: several researchers being elected to Fellowships, receiving Presidential awards, earning Meritorious Civilian Service awards, and many others.

Other highlights include engineers and researchers making significant discoveries in UAV capabilities, space science, fuel from seawater, hyper-cleansing, micro-materials, and coupled ocean/atmospheric models research.

Our community outreach programs continued to thrive during 2016, as our D.C. campus hosted its 50th annual Children's Holiday Party for more than 100 local elementary school children, as well as more than 50 local high school science teachers via our STEM Outreach Program.

We also had the pleasure of hosting more than 170 distinguished visitors – senior Navy leaders and other influential decision makers throughout the Department of Defense and industry – educating them on the significant research being conducted on the Lab throughout the year, emphasizing how important our work is in supporting the Navy and Marine Corps team.

Overall, 2016 was another busy year here at NRL, filled with a mixture of exciting new discoveries, methodical and systematic research, all while recognizing our people in an environment that fosters teamwork, collaboration, and intellectual curiosity.

As you read the *2016 NRL Review*, we hope you are as proud of our accomplishments as we are, excited and eager to explore what lies ahead in 2017.

We are advancing **further than you can imagine.®**

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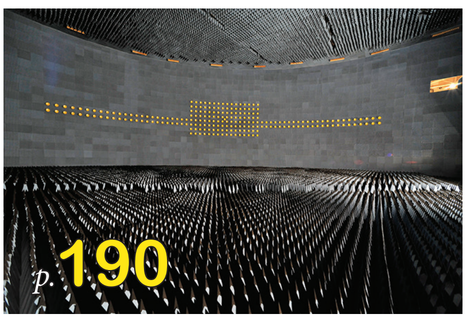
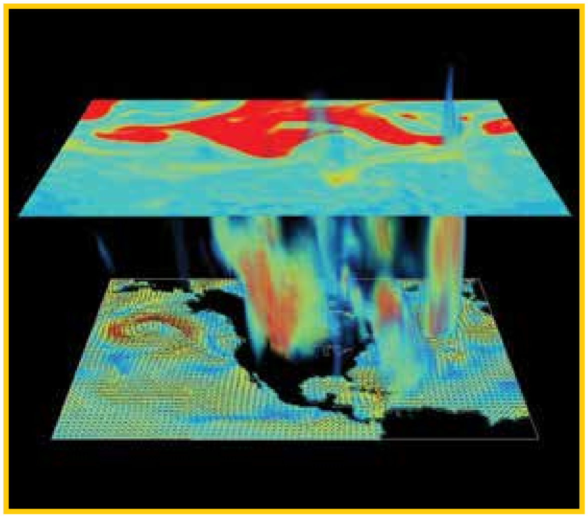


NRL's Involved!

NRL SCIENCE AS ART CONTEST

Commanding Officer Choice



Superstorm Sandy

Many forecasts of Hurricane Sandy in 2012 were off the mark. Looking at this three-dimensional image of one forecast, it's easy to see why. The image is based on a forecast of Sandy from the Coupled Ocean/Atmosphere Mesoscale Prediction System for Tropical Cyclones, or COAMPS-TC®, a computer prediction system developed at NRL. As the image shows, the planet harbors many weather systems with varying scales and speeds that can interact, making forecasting a tangled problem. The COAMPS-TC model calculates tropical storm forecasts with help from an adjoint modeling system that solves equations involving many variables and aspects of the weather systems that influence storms such as Sandy. In the last several years of operational predictions, COAMPS-TC has proven to provide forecasters with the most accurate forecasts in the world.

James Doyle and Clark Amerault
Marine Meteorology Division

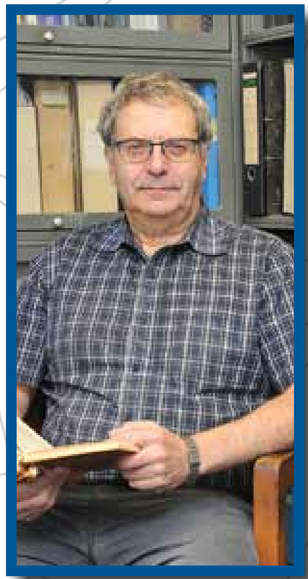
Our People Make a BIG Difference

The *NRL Review* dramatically illustrates the range of **research capabilities and innovative technologies** that make the U.S. Naval Research Laboratory a leader in so many fields. Driving all of NRL's innovations and successes are the **highly motivated people** who work here. It is these people who provide the talent, creativity, and sustained effort to **turn ideas into realities** in support of the Navy mission. In this section, we proudly highlight some of these special people.

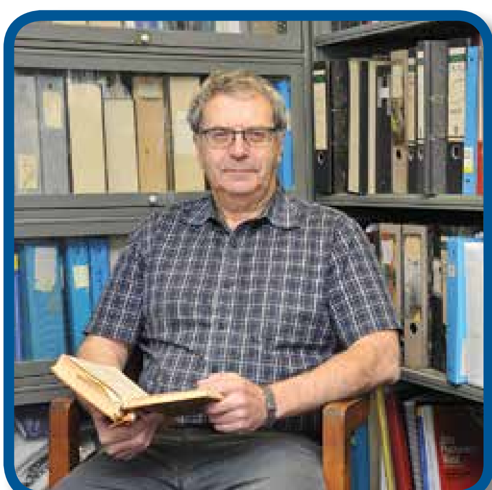









MS. JENNIFER CHESWICK is head of the Technical Services Branch in the Research and Development (R&D) Services Division. She earned her civil engineering degree from the New Jersey Institute of Technology in 2000, and she is a registered professional engineer in Maryland. She began her journey with the U.S. Navy as a Civil Engineer Corps Officer, serving both stateside and overseas, including tours of duty in Italy and Iraq. Her tenure as utilities officer for a mission-essential submarine tender homeported in La Maddalena, Italy, gave her a wealth of experience in equipment functionality and developing strategic short- and long-term solutions for mission success. Her work as utilities infrastructure project manager in Baghdad, Iraq, included helping to rebuild the badly damaged infrastructure that served the Iraqi people and the U.S. military mission. In Iraq, she also helped promote the local training efforts of the U.S. Department of State. Ms. Cheswick came to NRL in 2013 from the U.S. Department of Veterans Affairs, where her responsibilities as chief engineer for the New York Harbor Healthcare System included managing all aspects of operations, maintenance, capital improvements, safety, and environmental impact. Ms. Cheswick started her NRL career as the laboratory's energy manager, using her broad-reaching operations and facilities management experience to reduce NRL energy consumption without impacting the mission. She currently leads the Planning, Engineering and Environmental sections of R&D Services, where she oversees a staff responsible for designing in-house projects in support of research, managing the design and execution of Naval Facilities Engineering Command construction projects, and ensuring that all research and construction activities adhere to Navy planning and funding guidance as well as environmental laws and mandates. As a member of the Naval Research and Development Establishment facilities working group, she helps develop creative and effective solutions crucial to improving timetables for NRL facilities projects and providing the world-class laboratories necessary to continued growth and success of the NRL research community in its daily work.



DR. ALEXANDER EFROS is a research physicist in the Center for Computational Materials Science of the Materials Science and Technology Division. He received his Ph.D. in 1978 from St. Petersburg Technical University, Leningrad. He joined NRL as a contractor in 1993 and became an NRL staff member in 1999. His research focuses on optical, transport, and magnetic properties of nanoscale semiconductors and electron spin manipulation for spintronics and quantum information processing. He has made many pioneering contributions to the theory of nanocrystal quantum dots, and he established the basic model now used for describing their electronic and optical properties. The theory he helped develop has led to a new class of optical materials and a new form of matter commonly referred to as "artificial atoms," the nanocrystalline materials now considered a key element of modern nano-optics, nanophotonics, and optoelectronics. Many NRL experimental groups are exploring the possible use of quantum dots in important applications, one of the most exciting of which may be a tool for optically imaging the electrical activity of many neurons simultaneously. Dr. Efros maintains strong and rewarding connections with experimentalists both inside and outside NRL. "This is a very exciting time for scientists working in nanoscience research. I believe that collaborative research between experimentalists and theorists in the NRL Institute for Nanoscience will lead to significant technological breakthroughs that will affect the lives of many people, perhaps along similar lines to the blue-green light-emitting diodes a dozen years ago."

MS. APRIL MOORE is a financial and administrative management specialist (FAMS) in the Systems Analysis Branch of the Spacecraft Engineering Division. She began working at NRL in 2005 as a security assistant in support of visitor control, badging, and personnel security. She later joined Spacecraft Engineering as an office automation clerk and then received a promotion within the division to the position of superintendent secretary. In these roles, she provided financial and administrative support to a division with approximately 150 people. She also oversaw large division procurement requests, assisted the administrative officer with data calls, coordinated administrative processes with branch secretaries, and performed financial monitoring of two divisional multimillion dollar programs. In her current FAMS role, she has played a crucial part in supporting transparency of financial transactions between NRL and its sponsors while providing expertise that facilitates processes and assists project managers in their funding use. The primary ambition of her career at NRL, she says, is to make the administrative process as efficient as possible for NRL scientists and engineers, with the objective of maintaining a positive environment that allows everyone at NRL to thrive in their daily work and achieve the goals that make a long-lasting and global impact. "I love what I do and admire the work of my NRL coworkers. I particularly enjoy watching their idea become reality and then seeing it launched into space."

DR. FREDDIE SANTIAGO is an electronics engineer in the Remote Sensing Division. He started his NRL career in 2004 with the Remote Sensing Division in Albuquerque, New Mexico, under STEP (Student Temporary Employment Program), while also pursuing his M.S. degree in physics from the University of Puerto Rico, Mayaguez Campus. After five years with the U.S. Department of Energy, and on completion of his Ph.D. in electrical engineering (with an optoelectronics concentration) from the University of New Mexico in Albuquerque, he was hired as a full-time NRL employee in 2014 with the Remote Sensing Division in Washington, DC. He also became a Karles Fellow in 2014 and established the NRL Adaptive Polymer Lens Lab to study advanced polymers for optics. His research interests include adaptive and active optics, optical propagation through atmospheric turbulence, remote sensing, optical metrology, optical and mechanical design, and active/passive polymers for optical applications. Over the past few years, he has worked on a rapid adaptive zoom application based on adaptive polymer lenses and lightweight polymer optics for direct-view optics of small weapons and other military systems that require reduced size, weight, and power.

We are **explorers**

We are **futurists**

We are **protectors**

DR. ERIK TEJERO is a research physicist in the Space Experiments Section of the Plasma Physics Division. His areas of research include the dynamics of waves and particles in both ionospheric and magnetospheric plasmas. After completing his B.S. and M.S. degrees at the Massachusetts Institute of Technology, he worked for a year on the magnetized target fusion experiment at Los Alamos National Laboratory. He came to NRL in 2004 to work on the development of a low-power carbon nanotube emissive probe for space applications. He left NRL to complete his doctoral coursework at Auburn University and then returned to NRL in 2007 to conduct doctoral research in the Space Physics Simulation Chamber (SPSC), focusing on verification of electromagnetic ion cyclotron waves driven by transverse sheared flows. After obtaining his Ph.D. degree, he remained involved in NRL research as a Karles Fellow. He now manages much of the day-to-day operations of the SPSC, where he conducts experiments replicating basic physical processes of various ionospheric and magnetospheric phenomena. His work at NRL has included the experimental verification, characterization, and theory of electrostatic and electromagnetic transverse velocity shear-driven instabilities; experiments to directly measure the resonant interaction between energetic electrons and whistler waves and the resulting pitch-angle scattering; and experiments to demonstrate the electrostatic to electromagnetic transition of lower hybrid waves to whistler waves via nonlinear scattering off of thermal electrons. These efforts are important to the U.S. Navy's operations and understanding the dynamics of the natural space environment.

DR. LINDA THOMAS is an electronics engineer in the Electro-optics Technology Section of the Naval Center for Space Technology. She has been working at NRL since 2004. Her research interests are free-space laser communications, hybrid optical and radio frequency communications networks, satellite laser ranging, and single photon detectors. Dr. Thomas received her bachelor's degree in electrical engineering from Duke University and both a master's degree and a doctorate in the field of electrical engineering from the University of Maryland, College Park. She is an associate editor of the *Journal of Lightwave Technology* and prior conference chair of the SPIE Conference on Atmospheric Propagation. "My motivation is twofold. First, I want to be an honest broker. As a new NRLer, I was informally mentored by senior engineers and researchers from across the Laboratory. One of the best pieces of advice I was given was that our role here at NRL was to make sure decision makers had accurate information when making decisions about new technologies, systems, and architectures. In my work, I strive to be an honest broker, no matter how uncomfortable it may be sometimes. Second, I believe that engineering is a competitive sport. Friendly competition with other laboratories and Federally Funded Research and Development Centers is stimulating and helps keep the research community honest."

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DR. TEGAN WEBSTER is a research mathematician in the Advanced Signal Processing Section of the Radar Division. Dr. Webster joined NRL in 2011 under STEP (Student Temporary Employment Program) and became a full-time employee after obtaining her Ph.D. degree in mathematics in 2012 from Rensselaer Polytechnic Institute, where her research focused on multistatic polarimetric radar modeling, simulation, and imaging. At NRL, she has worked in programs involving phase-only multiple-input multiple-output radar transmit nulling to facilitate interoperability among radio frequency spectrum users and utilization of communications signals as signals of opportunity for distributed passive radar systems. Dr. Webster is currently the principal investigator for a 6.1 program that aims to improve the theoretical foundation of multistatic radar to better quantify and take advantage of the possible performance improvement that these radar systems may offer. The program involves the development of mathematical electromagnetic models and large-scale simulation environments to assess multistatic radar performance, the creation of processing and imaging techniques for multistatic radar data, and the validation of these models, simulations, and techniques through experiments. "The opportunity to work on a variety of topics in a collaborative work environment makes it possible to continue to grow as a researcher at NRL."

DR. HEMANTHA WIJESEKERA has been a research oceanographer in the Oceanography Division since 2008. Before joining NRL, he was an associate professor at Oregon State University and associate program director of the Physical Oceanography Program in the Geoscience Directorate at the National Science Foundation. He received a B.S. degree in mechanical engineering from the University of Moratuwa, Sri Lanka, in 1982, and both an M.S. degree in atmospheric sciences and a Ph.D. degree in oceanography from Oregon State University, in 1986 and 1992, respectively. He is a recognized expert in mesoscale to small-scale physical process, flow-topographic interactions, and air-sea interaction, particularly in oceanographic observations from towed, moored, and autonomous platforms. His work at NRL has focused on understanding and quantifying unresolved physical processes for the development of subgrid-scale parameterizations for U.S. Navy models. He recently completed a successful study of current flow interactions with a submerged bank in the northern Gulf of Mexico. He is also principal investigator of a 6.1 NRL core project on "Effects of Bay of Bengal Freshwater Flux on Indian Ocean Monsoon" and an Office of Naval Research Departmental Research Initiative (DRI) on "Flow Encountering Abrupt Topography." His efforts in the Bay of Bengal were critical to establishing an international research program of U.S., Indian, and Sri Lankan scientists. In the DRI on "Flow Encountering Abrupt Topography," he leads a major mooring field program over the Palau-Kyushu ridge in the Western Pacific Ocean that seeks to understand and quantify wakes, eddies, and the associated submesoscale phenomena when a large-scale flow encounters a combination of a steep ridge and a small island under a wide range of background ocean conditions. "I am grateful for the opportunities NRL has provided that allow me to take on the challenges of operating in remote regions of the world's ocean where our Navy has operational relevance and that offer the possibility of discovering new mechanisms that drive processes in the upper ocean and air-sea interaction on scales from millimeters to hundreds of kilometers."

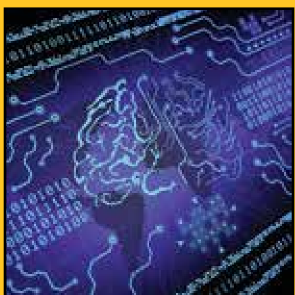
NRL established the Karles Fellowship in honor of Drs. Jerome and Isabella Karle, two scientists who have dedicated their entire professional lives to innovative advancements in science and technology. The Karles embody the intensity and fervor that NRL wishes to foster and harbor in the workforce of the future. Karles Fellowships are awarded to new NRL hires who are recent graduates and show exceptional scientific abilities and research potential. The Karles Fellowship is one element of NRL's Jerome and Isabella Karle Distinguished Scholar Fellowship Program, which also includes the Karles Senior Research Fellowship, open to established researchers whose credentials are comparable to those of the Karles, and the annual Karles Invitational Conference.

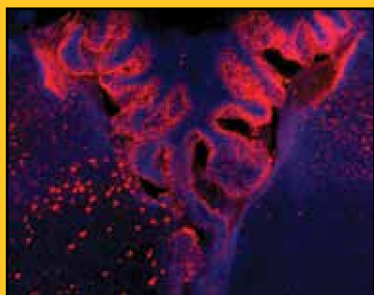
NRL Hosts Its Fifth Annual

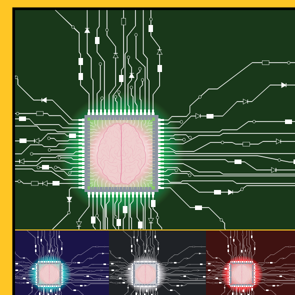
KARLES INVITATIONAL CONFERENCE

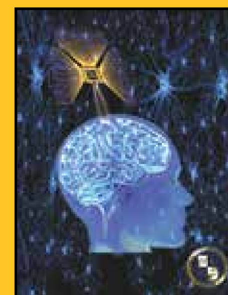
AUGUST 18–19, 2015

NEUROELECTRONICS









The U.S. Naval Research Laboratory (NRL) 2015 Karles Invitational Conference, held August 18–19 in Washington, D.C., highlighted current research and major international initiatives in neuroelectronics.

Against a backdrop of tremendous recent advances in understanding the brain and in cognitive architectures, two growing themes in electronics are how to make novel hardware that can efficiently implement brain-like algorithms and how to interface electronics with biological wetware. Technological breakthroughs in these areas of neuroelectronics are sure to have significant impact on both civilian and military applications in areas such as intelligent decision making, robotics, autonomous vehicles, automated image analysis, and the long-term treatment of battlefield trauma including paralysis, loss of limbs, and potentially even brain injury. At the Fifth Karles Invitational Conference, leading researchers in the field presented the outlook and prospects of this field for the coming decade and beyond.

The modern revolution in electronics, driven by ever more complex integrated circuits with ever decreasing geometries, has created a bootstrap effect in pioneering advances in both the physical sciences and the life sciences. The ability to perform massive computations with lightening speed has opened the way to a host of new technologies in this, the Information Age. However, for all of these developments in digital computation, the ability to do some of the most straightforward tasks performed by the human brain, such as near instantaneous image recognition, until recently has been elusive. This is changing as we achieve a better understanding of how the human brain processes information and our ability to interact with it through next-generation sensors and nanometer-scale precision probes. As neuroelectronics advances rapidly, the possibilities for new technological capabilities to aid society will be large.

The Karles Invitational Conference on Neuroelectronics was organized into four sessions: National and International Perspectives, Understanding the Brain, Mimicking the Brain, and Interfacing with Neural Systems, with discussions regarding the current state, challenges, and future of the field with invited audience participation from science and technology policy makers, sponsors, researchers, international experts, and technical society leaders.

Initiated by the U.S. Naval Research Laboratory (NRL) in 2010, the Karles Invitational Conference is an annual series in recognition of the distinguished career contributions of Dr. Jerome Karle, 1985 Nobel Laureate in Chemistry, and Dr. Isabella Karle, 1993 Bower Award Laureate and 1995 recipient of the National Medal of Science. Front row (l to r): Dr. John Montgomery, Rear Adm. Mathias Winter, Dr. Isabella Karle, Dr. Gerry Borsuk. Second row: Dr. Banahalli Ratna, Dr. Barry Horwitz, Capt. Mark Bruington, Dr. Monica Basco, Dr. Bhakta Rath, Ms. Anne Kusterbeck. Third row: Dr. Baruch Levush, Dr. Patrick Kanold, Dr. Eric Snow, Dr. John Mclean, Dr. Susan Greenfield, Kaushik Roy, Dr. Stephen Furber, Dr. Narayan Srinivasa. Fourth row: Dr. Terry Sejnowski, Dr. Richard Anderson, Dr. Tim Harris, Dr. Stanley Williams, Dr. Marcel Just, Dr. Garrett Stanley, Dr. Warren Grill, Dr. Bryan Jackson.

Jeffery Cleveland manages the Neptune® software, developed by the U.S. Naval Research Laboratory to manage satellites and ground antennas.

Neptune® Software from NRL Saves Money Across Multiple Rocket Satellite Missions

Jeffery Cleveland is on a mission to save the government a lot of money. The U.S. Naval Research Laboratory (NRL) uses a common software, called Neptune®, to fly all its satellite missions and manage its antennas on the ground. But Cleveland thinks Neptune could be even bigger. "It's a multi-mission command and control software, capable of flying virtually any satellite," says Cleveland. Kirtland Air Force Base is just one place that's already realized how using Neptune, instead of writing all new software for each mission, saves time and money on satellite operations.

Satellites aren't mass-manufactured; each is built to be unique for its mission. With such variance in hardware and in the data they collect, don't we also need unique software to run each one?

It turns out no. "NRL was in satellites before anybody was in satellites; what they quickly found is that they can't keep reinventing the wheel," says Cleveland. NRL has been flying satellites out of the Blossom Point ground station in Maryland for over 50 years. "Blossom Point has some serious antennas and some serious capability," he says. "We can handle almost any number of satellites, any kinds of satellites, any orbits; Neptune is the software that does that."

NRL's innovation was to realize that, while satellite payloads vary widely, they almost all ride on buses that do the same few things. "The satellite bus is sort of the infrastructure: it handles power, it handles heating and cooling, it handles communications," says Cleveland.

The Neptune software uses a common software for the functions that every mission does, and then project engineers tailor it to the mission. "There's always mission-specific software, there's always something that needs to be added," says Cleveland, "so you have interfaces at the right places, well-managed interfaces, that allow you to do that."

This saves a lot of money in development and maintenance. "A lot of places, the government buys a system from the space on down to the ground," says Cleveland. "I worked at one site where there's a family of four satellites; two are operated by one ground system and two are operated by a completely different, incompatible ground system." That means the government is missing out on the efficiencies that would come with a common approach.

In addition to operating satellites, the Neptune software can also manage the ground station antenna array. Traditionally, one antenna listens for one satellite, so it's not in use most of the time. "LEO [low Earth orbit] missions in particular, you have a 10 to 15 minute contact, and then you go away for 90 minutes," says Cleveland. "And just down the street, there might be another antenna, same capability, sitting idle — why do we keep doing that?"

So in 2013, NRL demonstrated how an Air Force satellite operations center (SOC) in New Mexico could, by using the Neptune software, use existing antennas at Blossom Point. "We came up with a capability that allows different SOCs to share resources," says Cleveland.

Cleveland hopes the Neptune software will help advance satellite research more quickly, and at less cost. "If you're the government," he says, "the game is to take as much use of the common software as possible, and minimize the mission-unique software as much as possible."

Busting apart data: Neptune software takes advantage of commonalities

Every satellite collects and sends down data that needs to be decommutated out of binary code. "That conversion is something that everybody does," says Cleveland, "so that's in the common software: collecting, logging, storing, decommutating, and alarm checking."

The Neptune software does need to be configured for each mission. "It gets down to, you have to tell us what your 1s and 0s mean, and how we can make them into engineering values," says Cleveland. "We have a way for [the user] to define, with a simple Excel spreadsheet or database, this is what my telemetry looks like," he says.

The initial setup can be intensive —"But that's because this is rocket science," he says. Once done, however, the Neptune software makes it easy for onsite operators to make modifications. "They're the ones that know the spacecraft, they're the ones that know what to do," says Cleveland. As an example, "I know this heater is flaky and so I don't want the temperature sensor to go off at 50 degrees Celsius anymore, I want it to go off at 60 because the temperature's creeping up and that's okay, we're watching that."

This is very different from traditional, mission-unique software, where the SOC has to go back to the contractor for modifications, which is costly and time-consuming. Using traditional software is like wanting to change your default page margins from one inch to one-and-a-quarter — and then having to hire a team of engineers to come to your home and install a new operating system.

"What we're doing, by isolating the common stuff and some mission-unique software, we're giving the local engineers the power to do their job themselves right there," says Cleveland. "We just teach them how to put that into a script or modify a database entry and they're done; they never call us, they take care of it themselves."

Better CubeSats with a standard bus and common antennas?

Nowhere is cost savings more important than with CubeSats. CubeSats started becoming popular about ten years ago, as a way for universities and labs to cheaply try out innovative ideas. They're often launched with much bigger satellite missions, packed into the extra space in the rockets. "CubeSats are going to change the world for sure — but that's the payload," says Cleveland.

Cleveland sees people too readily accepting failure from CubeSat missions, because they're perceived as inexpensive and high-risk. "I think the numbers would say we're not contacting way more than we should be contacting," he says.

He thinks that if sponsors worked with experts to provide a standard bus, keeping the innovation to the payload — "we'll get you your data, you do the cool payload" — more missions would be successful and research would advance faster.

He'd also like for sponsors to combine ground capabilities into one high-power station, like a Blossom Point, instead of using much lower-capability antenna networks. "You can't cheap out on the ground," Cleveland says, "because once it's up, it's a satellite; the laws of physics don't know CubeSats from anything else. You've got to communicate, you've got to stay up in orbit, you've got to find them."

The initial contact with a satellite right after launch is hard; space is vast, and there's always some cone of uncertainty. "Even on NRL missions, we've launched some very massive things; and it's hard to separate, that's the spacecraft, that's the launch vehicle," he says. It's even more difficult with CubeSats, which are too small for much of a radar return and send only very low-power transmissions. "There's a lot of CubeSats that are never contacted, and they write that off as, 'Oh, well the bus never turned on,'" says Cleveland, "when I think of a lot of it is, it was talking over here and you were listening next door and just missing it."

NRL could help significantly improve the success of CubeSats. "What NRL brings to the table is the ops experience and our innovative software to do command and control, so that you don't have to worry about that," says Cleveland.

The U.S. Naval Research Laboratory (NRL) has been flying satellites out of the Blossom Point ground station in Maryland for over 50 years, using a multi-mission software called Neptune®.

Neptune software demonstrated SOC2SOC and how to learn from failure

As an example, Kirtland Air Force Base used the Neptune software for the Space Environmental NanoSatellite Experiment (SENSE), the launch of two CubeSats in 2013. It was NRL's first demonstration of sharing antennas between two different SOCs, a capability Cleveland calls SOC2SOC.

NRL was configuring the Neptune software for the SENSE mission and asked if they could also use it to just test out SOC2SOC. "But it turned out that on launch day, the antenna the SENSE program had, it wasn't able to command, it didn't work," says Cleveland. "And so they contacted Blossom Point." Thanks to this resource-sharing "test," the Air Force continued to get telemetry for the next 18 months (until the satellite deorbited). And even though the satellites had problems, by being able to contact the bus, "you get a lot more valuable feedback, and so that can go into improving the next mission."

Though NRL configured the Neptune software for SENSE operations, it was a group of Air Force lieutenants they taught to run it. "These guys were fantastic to work with, they got what we were trying to do and it was fun," says Cleveland. "They came up with the testing, they came up with the displays, they did the ops."

SENSE is also a good example of how Blossom Point can be used as a ground station by an SOC run remotely from computers somewhere else. "[Kirtland] has been great to work with, and I'd like to see more of that continue," says Cleveland.

Being a part of choosing responsible solutions

Cleveland has managed the Neptune software for NRL since 2011; though he's been at NRL since 1984, when he graduated from Penn State with the university's first computer engineering degree. "I like integration and testing, I like to find out what's wrong," he says.

He's supported innumerable launches, including Clementine, TacSat4, and WindSat. "I like to think that I'm a rocket scientist," he says. "I've been at the bottom of the tower when the rocket's going off, I've had some great experiences." He's now working on a major operations improvement to the Kirtland Air Force Base SOC.

In Cleveland's office, pictures from previous Neptune missions are tacked up right alongside his son's drawings of space. His son is now nine. "He's curious and interested, so it's kind of fun to talk about what I do," says Cleveland. "We've gone stargazing and I've talked to him about satellites and what I do. He doesn't have a detailed understanding, but satellites are cool and he knows his dad works on satellites — so that's pretty cool."

One thing Cleveland appreciates about NRL is the mission focus. "When we find problems, what I really liked is there wasn't a lot of finger pointing. It was like, what is this, you figure it out, find out where it is."

He brings that mission focus to the Neptune team, making sure that mission success is the priority. "One of my favorite quotes is, 'Better is the enemy of good enough,'" he says, "which is not a copout to doing a quality job, but the importance of knowing what you want to do and stopping when you've done it."

He hopes the Neptune software will transform the satellite industry. "I like getting to other places and saving other people money," he says. "I'm happy when they choose responsible solutions, and I think we're a part of that."

A Rubber That Stops Corrosion?

NRL Research May Extend Life of Amphibious Assault Vehicles (AAVs)

Dr. Ray Gamache (left) and Dr. Mike Roland (right) of the U.S. Naval Research Laboratory.

The U.S. Naval Research Laboratory (NRL) has found that some types of rubber provide corrosion protection — and potentially better ballistic protection — for amphibious assault vehicles (AAVs). This is important to the U.S. Marine Corps (USMC) as they look to extend the AAV, introduced in 1972, through 2035. “Innovative sustainment concepts, like those NRL is investigating, enable us to avoid the cost of new design, development, and production of new components,” says Tim Bergland of the USMC Advanced Amphibious Assault (AAA) office.

Dr. Mike Roland and Dr. Ray Gamache led the research for NRL. “What makes [AAVs] unique is they can go in water and on land,” says Roland. “They give the Marine Corps a capability that no other service has.”

Since the 1990s, the USMC has been bolting armor onto their AAVs. “The armor itself is a laminate of high hard steel, which by itself is good for ballistics; a rubber layer; then there’s another soft steel layer in the back,” says Roland. The problem is that the armor gets corroded with intense use and exposure to salt water.

Roland and Gamache found rust and corrosion start at cracks in the paint. “You’ve got steel, rubber, steel—and these things are thermally expanding and contracting differently,” says Roland. “In addition to which, AAVs aren’t driven like expensive Volvos; they’re banging into stuff — and now you’ve got a way for water ingress.”

Amphibious assault vehicles (AAVs) demonstrate ship-to-shore connector capabilities at Camp Pendleton. (Photo: USMC)

NRL showed that certain types of rubber, called polyureas, could better protect the armor from corrosion by stretching with it, instead of cracking like brittle paint. They also showed polyurea coatings slow bullets and blast fragments. “They take kinetic energy from the bullet,” says Roland. “So the bullet, to keep penetrating, it’s meeting an increasingly resistant medium. And if it slows down enough — it always makes it to the steel plate, but it doesn’t have enough velocity to get through it.”

NRL’s research could help extend the life of today’s AAVs, and may also guide the next generation of ship-to-shore connectors. “We solved the corrosion problem,” says

Roland. "And with a negligible increase in weight, we also provided a higher payload capacity and the potential for better ballistic protection."

Corrosion protection: polyurea coatings don't crack like paint

By exposing steel test pieces to salt water in their lab, Roland and Gamache showed that polyurea protects armor from corrosion much better than paint does.

The U.S. Naval Research Laboratory coated steel samples of amphibious assault vehicle armor with paint or polyurea, bent some of them, and exposed them to salt water at its Key West corrosion testing facility. On the bent pieces, "the paints tend to crack," says Dr. Mike Roland, who led the project. "The polyureas don't because they're elastomeric, rubbery."

"We wanted to simulate what happens in the field, so we bent some of the test pieces," says Roland. In addition to flat test pieces, "we had a gentle bend and we had a 90° acute bend." They tested five coatings: two types of paint, a polyurea NRL has been using in other armor applications, and two polyureas developed by a private company. "We set up aquarium tanks filled with sea water. We raised the temperature to 40 and 50 degrees centigrade [104 and 122 °F], just to accelerate the corrosion, and we bubbled air so there was plenty of oxygen."

The polyurea worked much better than paint. "If you just put the plate in flat, they'll all work," says Roland. But with the bent pieces, "the paints tend to crack. The polyureas don't because they're elastomeric, rubbery; so they stretch and don't open up a pathway for the water."

While having a long-term solution is very important, the USMC also needs to know how best to maintain the AAVs in use now. "We quantified how much they're going to lose, in ballistic performance, with the corrosion," says Roland. "This will guide the Marine Corps as to when they need to replace or repair the armor, saving a lot of money."

NRL continues to monitor samples in actual seawater troughs at NRL's Key West corrosion testing facility. "The ones that performed the best in salt water tanks in the lab are performing best at Key West," says Roland.

"The best of both worlds": how is polyurea stretchy and so tough?

Polyureas aren't as common as conventional rubbers; but if you've seen a pickup truck bed-liner, you've seen a polyurea. Conventional rubbers, polyurethanes, are isocyanate covalently reacted with an alcohol. "But if you react [isocyanate] with an amine, you get urea," says Roland. "Polyurea is better because it's got a lot more hydrogen bonding."

The hydrogen bonds are weak, compared to covalent bonds, so they break first. "That'll alleviate stress," says Roland, "and maybe your covalent bonds, the polymer chains themselves, remain intact. And the beauty of the hydrogen bonds is they'll reform; so when you remove the load, you don't have any permanent damage." That makes it multi-hit capable.

"In conventional materials, you can have something that's really stiff but doesn't stretch much; or you can have something really soft, like silly putty, and it stretches a lot," says Roland. "Polyureas, they can stretch to 10 times their original length, but the force it takes to do that is enormous — so you get toughness, the best of both worlds."

Basic research prepares NRL to solve the military's applied problems

After completing his Ph.D. in physical chemistry at Penn State, Roland worked for a rubber company and then joined NRL in 1986. "Most of our [basic research] is making dielectric measurements under extreme pressure and temperature conditions," he says, "so we're looking at how molecules move." He's often asked why the Department of Defense would fund that kind of research.

"Elastomer applications for armor have to do with perturbing [molecules] faster than they can move. Well, how do we know how they move? It's the kind of studies we've been doing for 20 years — basic science, publishing papers — that gives us the background to understand, when we get an elastomer-coated armor, why certain rubbers work and others don't." Or gives them the ability to creatively solve a corrosion problem, with polyurea, instead of limiting the focus to paint.

Roland thinks NRL's basic research is one of its core strengths. "That's what enables NRL to attract really good people, because often coming out of grad school with a Ph.D., people want to do basic science," he says. "It's only after being exposed to applied problems that they find, hey this is really fun, I can actually see something I've done — like this armor."

DoD Lab Day

NRL Demonstrates Groundbreaking Technologies

U.S. Naval Research Laboratory scientists are trying to understand how blast waves interact with helmets and body armor so that men and women in uniform can be better protected against traumatic brain and other injuries.

The U.S. Naval Research Laboratory (NRL) demonstrated some of its groundbreaking technologies at the first ever Department of Defense (DoD) Lab Day, held at the Pentagon in Washington, D.C. on May 14, 2015. The goal of the event was to increase awareness of DoD laboratory research projects and technology innovations with Pentagon senior leaders, members of Congress, participating local high school students, news media, and DoD employees.

"NRL is a place where the basic research for the next generation of capabilities is getting done — but we're also applying that knowledge, right now, to solve problems for today's fleet," says Captain Mark Bruington, Commanding Officer of NRL. "You want a tougher armor, a better awareness of what's over your horizon? At NRL, we're doing that."

DoD Lab Day is designed to increase understanding of the complexity and diversity of defense laboratories. The products of 38,000 scientists and engineers at more than 60 labs across 22 states provide vital support to many missions, including global disaster relief and peacekeeping efforts.

NRL — along with the Army, Marine Corps, Air Force, and medical organizations—provided visitors with a rare look at more than 100 innovations that are advancing the capabilities of our nation's military. Many of these innovations were sponsored by the Office of Naval Research and other funding organizations.

"The nation's top scientists come here and they stay here because the work is rewarding," says Dr. John Montgomery, Director of Research at NRL. "We bring together the best minds and give them the freedom they need to pursue these wild and interesting ideas. They collaborate with each other, and they form close relationships with the warfare centers and military users — that's where the real innovation and game-changing solutions catch fire."

NRL is advancing research in the areas most of interest to the Navy and Marine Corps, including autonomous and unmanned systems, alternative energy, information dominance, power projection, and warfighter performance. Providing the men and women in harm's way with what they need is one way to keep America and her allies always at the advantage, and NRL is proud of its 90-year legacy.

At DoD lab day, NRL demonstrated:

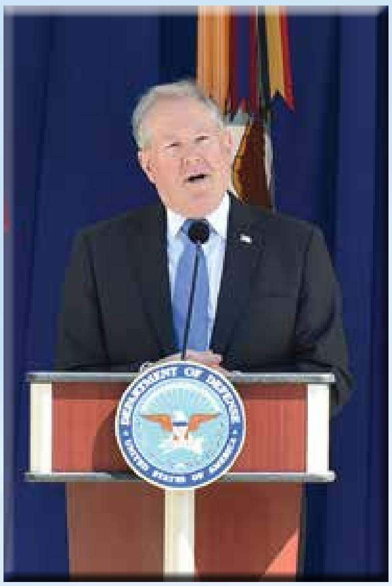
Vantage: an airborne, unmanned platform to support electronic warfare and intelligence, surveillance, and reconnaissance missions.

CICADA: an unmanned glider, nearly undetectable, that delivers payloads to precise waypoints.

Helmet Modifications to Mitigate Traumatic Brain Injury (TBI): DoD is providing the best possible equipment to warfighters, but NRL is always looking for better solutions.

WindSat: a large satellite, in orbit today, that provides ocean surface wind vecotor measurements and other environmental parameters to help weather predictions.

Principal Deputy, Assistant Secretary of Defense for Research and Engineering, Alan Shaffer spoke at the opening ceremony for DoD Lab Day.



The event was hosted by Mr. Frank Kendall, the Under Secretary of Defense for Acquisition, Technology, and Logistics.

Vantage

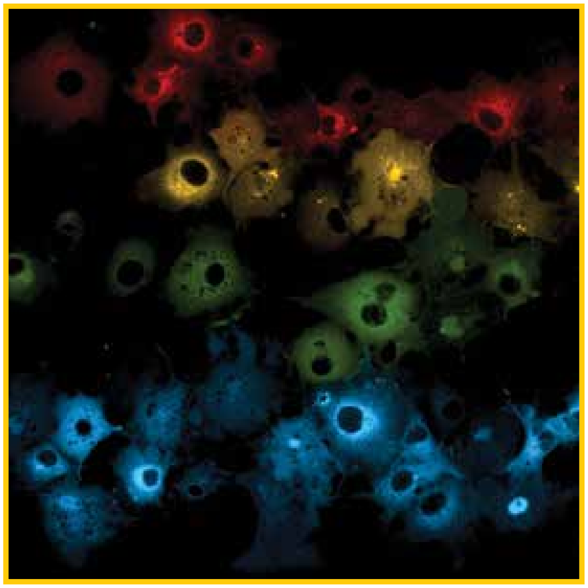
CICADA

Helmet Modifications to Mitigate TBI

WindSat

The Naval Research Laboratory

NRL SCIENCE AS ART CONTEST
Director of Research Choice



Quantum Dots: A Rainbow of Colors

This is an image of quantum dots, tiny bits of semiconductors just a few nanometers in diameter. A billion of them could fit on the head of a pin. Because they're so tiny, quantum dots have some unusual materials properties — especially electrical and optical ones — thanks to the quantum effects that kick in at smaller size scales. The color and brightness of the dots comes from their tunablity, i.e., researchers can pretty much tune the dots to emit whatever frequency of visible light they need for a given application, simply by altering the size of the dots. The most obvious application is using quantum dots as an alternative to the organic dyes used to tag reactive agents in fluorescence-based biosensors.

Lauren Field, James Delehanty, Kimihiro Susumu, and Igor Medintz
Center for Bio/Molecular Science and Engineering

NRL — OUR HERITAGE

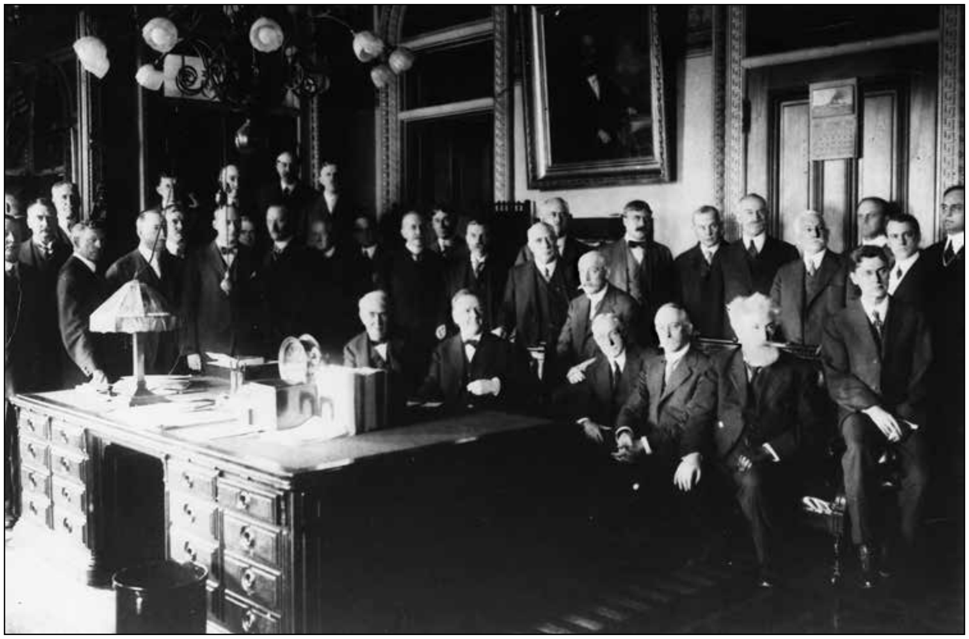
The early 20th century founders of the Naval Research Laboratory (NRL) knew the importance of science and technology in building naval power and protecting national security. They knew that success depended on taking the long view, focusing on the long-term needs of the Navy through fundamental research. NRL began operations on July 2, 1923, as the United States Navy's first modern research institution, and it continues today as one of the Navy's premier research and development centers.

Thomas Edison's Vision: The first step came in May 1915, a time when Americans were deeply worried about the great European war. Thomas Edison, when asked by a *New York Times* correspondent to comment on the conflict, argued that the Nation should look to science. "The Government," he proposed in a published interview, "should maintain a great research laboratory....In this could be developed...all the technique of military and naval progression without any vast expense." Secretary of the Navy Josephus Daniels seized the opportunity created by Edison's public comments to enlist Edison's support. He agreed to serve as the head of a new body of civilian experts — the Naval Consulting Board — to advise the Navy on science and technology. The Board's most ambitious plan was the creation of a modern research facility for the Navy. Congress allocated $1.5 million for the institution in 1916, but wartime delays and disagreements within the Naval Consulting Board postponed construction until 1920.

The Laboratory's two original divisions — Radio and Sound — pioneered in the fields of high-frequency radio and underwater sound propagation. They produced communications equipment, direction-finding devices, sonar sets, and perhaps most significant of all, the first practical radar equipment built in this country. They also performed basic research, participating, for example, in the discovery and early exploration of the ionosphere. Moreover, the Laboratory was able to work gradually toward its goal of becoming a broadly based research facility. By the beginning of World War II, five new divisions had been added: Physical Optics, Chemistry, Metallurgy, Mechanics and Electricity, and Internal Communications.

World War II Years and Growth: Total employment at the Laboratory jumped from 396 in 1941 to 4400 in 1946, expenditures from $1.7 million to $13.7 million, the number of buildings from 23 to 67, and the number of projects from 200 to about 900. During WWII, scientific activities necessarily were concentrated almost entirely on applied research. New electronics equipment — radio, radar, sonar — was developed. Countermeasures were devised. New lubricants were produced, as were antifouling paints, luminous identification tapes, and a sea marker to help save survivors of disasters at sea. A thermal diffusion process was conceived and used to supply some of the ^{235}U isotope needed for one of the first atomic bombs. Also, many new devices that developed from booming wartime industry were type tested and then certified as reliable for the Fleet.

The Naval Research Laboratory was conceived in 1915 during a correspondence between the Secretary of the Navy, Josephus Daniels (seated at his desk on the right), and Thomas Edison, who is shown here standing at his desk.



The Naval Consulting Board and Navy Department officials surround Thomas Edison and Josephus Daniels, who are seated behind the desk.

Secretary Daniels breaks ground for Building 1 in 1920.

Post-WWII Reorganization: The United States emerged into the postwar era determined to consolidate its significant wartime gains in science and technology and to preserve the working relationship between its armed forces and the scientific community. While the Navy was establishing its Office of Naval Research (ONR) as a liaison with and supporter of basic and applied scientific research, it was also encouraging NRL to broaden its scope and become, in effect, its corporate research laboratory. There was a transfer of NRL to the administrative oversight of ONR and a parallel shift of the Laboratory's research emphasis to one of long-range basic and applied investigation in a broad range of the physical sciences.

However, rapid expansion during WWII had left NRL improperly structured to address long-term Navy requirements. One major task — neither easily nor rapidly accomplished — was that of reshaping and coordinating research. This was achieved by transforming a group of largely autonomous scientific divisions into a unified institution with a clear mission and a fully coordinated research program. The first attempt at reorganization vested power in an executive committee composed of all the division superintendents. This committee was impracticably large, so in 1949, a civilian director of research was named and given full authority over the program. Positions for associate directors were added in 1954, and the laboratory's 13 divisions were grouped into three directorates: Electronics, Materials, and Nucleonics.

The Breadth of NRL: During the years since World War II, the Laboratory has conducted basic and applied research pertaining to the Navy's environments

NRL in its first year, 1923. Building 1, which housed the Laboratory's first research spaces, stands by itself on the left. Starting from the bank of the Potomac River and forming a line opposite Building 1 is the coal-fired power station, pattern shop, foundry, and machine shop.

NRL in the 21st century. In its more than 90 years, NRL has evolved into a large research and development campus with some 100 buildings and nearly 2500 full-time employees, more than half of which hold master's or doctoral degrees.

of earth, sea, sky, space, and cyberspace. Investigations have ranged widely — from monitoring the Sun's behavior, to analyzing marine atmospheric conditions, to measuring parameters of the deep oceans. Detection and communication capabilities have benefited by research that has exploited new portions of the electromagnetic spectrum, extended ranges to outer space, and provided a means of transferring information reliably and securely, even through massive jamming. Submarine habitability, lubricants, shipbuilding materials, firefighting, and the study of sound in the sea have remained steadfast concerns, to which have been added recent explorations within the fields of virtual reality, superconductivity, biomolecular science and engineering, and nanotechnology.

The Laboratory has pioneered naval research into space — from atmospheric probes with captured V-2 rockets, through direction of the Vanguard project (America's first satellite program), to inventing and developing the first satellite prototypes of the Global Positioning System (GPS). Today, NRL is the Navy's lead laboratory in space systems research, as well as in fire research, tactical electronic warfare, microelectronic devices, and artificial intelligence.

The consolidation of NRL and the Naval Oceanographic and Atmospheric Research Laboratory, with centers at Bay St. Louis, Mississippi, and Monterey, California, added critical new strengths to the Laboratory. NRL now is additionally the lead Navy center for research in ocean and atmospheric sciences, with special strengths in physical oceanography, marine geosciences, ocean acoustics, marine meteorology, and remote oceanic and atmospheric sensing.

The Twenty-First Century: The Laboratory is focusing its research efforts on new Navy strategic interests in the 21st century, a period marked by global terrorism, shifting power balances, and irregular and asymmetric warfare. NRL scientists and engineers are working to give the Navy the special knowledge, capabilities, and flexibility to succeed in this dynamic environment. While continuing its programs of basic research that help the Navy anticipate and meet future needs, NRL also moves technology rapidly from concept to operational use when high-priority, short-term needs arise — for pathogen detection, lightweight body armor, contaminant transport modeling, and communications interoperability, for example. The interdisciplinary and wide-ranging nature of NRL's work keeps this "great research laboratory" at the forefront of discovery and innovation, solving naval challenges and benefiting the nation as a whole.

NRL TODAY

ORGANIZATION AND ADMINISTRATION

The Naval Research Laboratory is a field command under the Chief of Naval Research, who reports to the Secretary of the Navy via the Assistant Secretary of the Navy for Research, Development and Acquisition.

Heading the Laboratory with joint responsibilities are CAPT Mark C. Bruington, USN, Commanding Officer, and Dr. Edward R. Franchi, Acting Director of Research. Line authority passes from the Commanding Officer and the Director of Research to three Associate Directors of Research, the Director of the Naval Center for Space Technology, and the Associate Director for Business Operations. Research divisions are organized under the following functional directorates:

- Systems
- Materials Science and Component Technology
- Ocean and Atmospheric Science and Technology
- Naval Center for Space Technology

The *NRL Fact Book*, published every two years, contains information on the structure and functions of the directorates and divisions.

NRL operates as a Navy Working Capital Fund (NWCF) Activity. All costs, including overhead, are charged to various research projects. Funding in FY15 came from the Chief of Naval Research, the Naval Systems Commands, and other Navy sources; government agencies such as the U.S. Air Force, the Defense Advanced Research Projects Agency, the Department of Energy, and the National Aeronautics and Space Administration; and several nongovernment activities.

PERSONNEL DEVELOPMENT

At the end of FY15, NRL employed 2626 persons — 32 officers, 56 enlisted, and 2538 civilians. In the research staff, there are 891 employees with doctorate degrees, 429 with master's degrees, and 583 with bachelor's degrees. The support staff assists the research staff by providing administrative support, computer-aided design, machining, fabrication, electronic construction, publication and imaging, personnel development, information retrieval, large mainframe computer support, and contracting and supply management services.

Opportunities for higher education and other professional training for NRL employees are available through several programs offered by the Employee Relations Branch. These programs provide for graduate work leading to advanced degrees, advanced training, college course work, short courses, continuing education, and career counseling. Graduate students, in certain cases, may use their NRL research for thesis material.

For non-NRL employees, several postdoctoral research programs exist. There are also agreements with several universities for student opportunities, as well as summer and part-time employment programs. Summer and interchange programs for college faculty members, professional consultants, and employees of other government agencies are also available. These programs are described in the *NRL Review* chapter "Programs for Professional Development."

NRL has active chapters of Women in Science and Engineering (WISE), Sigma Xi, Toastmasters International, and the Federal Executive and Professional Association. An amateur radio club, a drama group, and several sports clubs are also active. NRL has a Recreation Club that provides gymnasium and weight-room facilities. NRL also has an award-winning Community Outreach Program. See "Programs for Professional Development" for details on all these programs and activities.

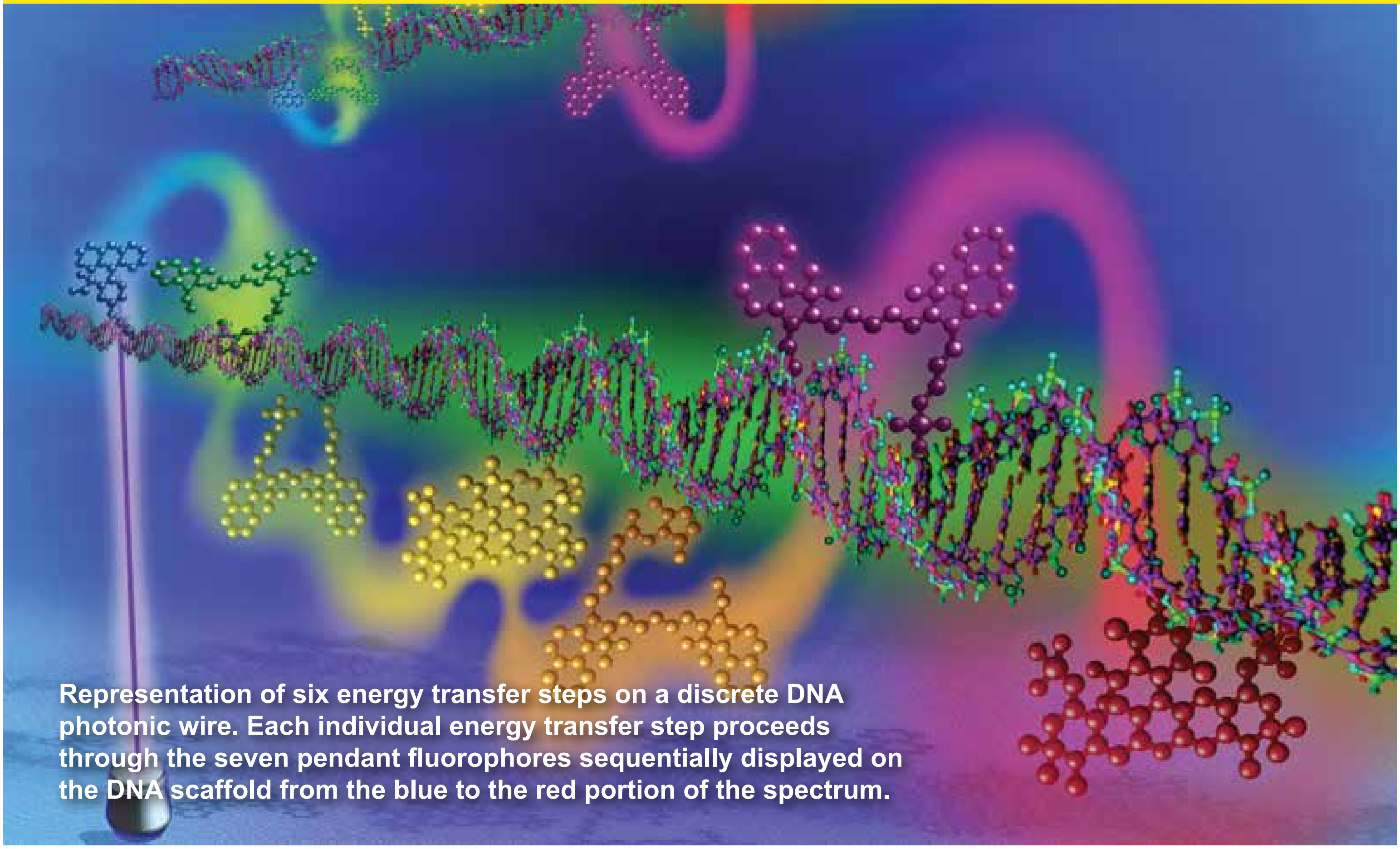
NRL has its very own credit union. Established in 1946, NRL Federal Credit Union (NRLFCU) is a sound financial institution that serves over 22,000 members including NRL employees, contractors, select employee groups and their families as well as consumers via the American Consumer Council. Focusing on its mission of Trusted Partners for Life, NRLFCU provides many free and low-cost products and services including free checking with free bill pay, Visa CheckCard, and mobile banking with remote deposit, auto and personal loans, credit cards, mortgages, and more. NRLFCU offers direct deposit, online access, and local branches (including one in Bulding 222, one in Waldorf, MD, and one in Alexandria, VA). Additionally, members have nationwide access via the National Shared Branch Network program, as well as surcharge-free access to over 335,000 ATMs via particpating networks. NRLFCU also offers personalized full-service investment and brokerage services. For more information, call 301-839-8400 or visit nrlfcu.org.

Public transportation to NRL is provided by Metrobus. Metrorail service is three miles away.

SITES AND FACILITIES

NRL's main campus in Washington, D.C., consists of 90 main buildings on about 131 acres. NRL also maintains 15 other research sites, including a vessel for fire research and a Flight Support Detachment. The many diverse scientific and technological research and support facilities are described here. More details can be found in the *NRL Major Facilities* publication at www.nrl.navy.mil.

Institute for Nanoscience



Representation of six energy transfer steps on a discrete DNA photonic wire. Each individual energy transfer step proceeds through the seven pendant fluorophores sequentially displayed on the DNA scaffold from the blue to the red portion of the spectrum.

The revolutionary opportunities available in nanoscience and nanotechnology led to a National Nanotechnology Initiative in 2001. In that same year, the NRL Institute for Nanoscience was established. The prospect for nanoscience to provide a dramatic change in the performance of materials and devices was the rationale for identifying this emerging field as one of the Department of Defense strategic research areas for basic research funding on a long-term basis.

The mission of the NRL Institute for Nanoscience is to conduct highly innovative, interdisciplinary research at the intersections of the fields of materials, electronics, chemistry, and biology in the nanometer size domain. The Institute exploits the broad multidisciplinary character of the Naval Research Laboratory to bring together scientists with disparate training and backgrounds to pursue common goals at the intersection of their respective fields in systems at this length scale. The Institute provides the Navy and DoD with scientific leadership in this complex, emerging area and identifies opportunities for advances in future defense technology. NRL's nanoscience research programs and accomplishments directly impact nearly all Naval S&T focus areas.

The Institute's current research program emphasizes multidisciplinary, cross-division efforts in a wide range of science and technology applications:

- Ultra-low-power electronics
- Quantum information processing
- Chemical signaling
- Energy conversion/storage
- Photonics/plasmonics
- Multifunctional materials
- Biomimetics
- Bio/inorganic hybrid materials

The Institute for Nanoscience building, opened in October 2003, provides NRL scientists access to state-of-the-art laboratory space and fabrication facilities. The building has 5000 ft^2 of Class 100 clean room space for device fabrication, 4000 ft^2 of "quiet" lab space with temperature controlled to ±0.5 °C, acoustic isolation at the NC35 standard (35 dB at 1 kHz), floor vibration isolation to <150 μm/s rms at 10 to 100 Hz and <0.3 mOe magnetic noise at 60 Hz, and 1000 ft^2 of "ultra-quiet" laboratory space with temperature controlled to ±0.1 °C and acoustic isolation at the NC25 standard

(25 dB at 1 kHz). Equipment includes a complete suite of fabrication tools including deposition and etch systems, optical mask aligners, two electron beam writers, a three-dimensional nanolithography tool, a focused ion beam writer, an optical pattern generator for mask making, a plasma-enhanced atomic layer deposition system, a laser machining tool, and a wide variety of characterization tools including an aberration-corrected transmission electron microscope.

Institute for Nanoscience clean room.

The Institute for Nanoscience research building.

Radar

NRL has gained worldwide renown as the "birthplace of U.S. radar" and for nearly a century has maintained its reputation as a leading center for radar-related research and development. A number of facilities managed by NRL's Radar Division continue to add to this reputation.

A major Division asset is the Antenna and Radar Cross Section (RCS) Measurement Facility capable of characterizing the radiation and impedance properties of antenna systems, performing RCS measurements, and measuring the s-parameters of RF-system components. This facility consists of two separate measurement resources, a compact range and an anechoic chamber, each providing multiple measurement options for frequencies in the range of 2 to 110 GHz. The compact range reflector simulates far-field conditions in a cylindrical quiet zone (phase error < 10°) with an 8 ft diameter and 8 ft length for RCS measurements and also has a near-field scanner capable of planar, cylindrical, or spherical nearfield antenna characterizations. The anechoic chamber provides far-field antenna patterns and s-parameter measurements of RF system components and has a second smaller near-field scanner for antenna characterizations.

Another significant Division asset is the Computational Electromagnetics (CEM) Facility, which supports complex, high-fidelity electromagnetic modeling of naval platforms, targets, and antennas. The facility produces detailed estimates of the radar cross section of ships. The Radar Division developed the Radar Target Signature (RTS) model specifically for calculating the radar signature of ships in a sea multipath environment. RTS calculates the radar signatures of large objects using computer models that describe the geometry and material properties of the objects. The radar signature of smaller objects, such as phased array antennas, can be accurately calculated using any of several low frequency computational electromagnetic software packages available within the facility. The facility contains a Linux cluster of 75 Apple Mac Pro computers with a total of 840 processors and 3.4 TB of physical memory. The CEM Facility also has multiple-CPU supercomputers used to design phased array antennas. This provides for tremendous synergism between the CEM group and the Antenna and Radar

Cross Section Measurement Facility. Innovative and novel designs generated in the CEM environment transition immediately for assessment in the compact range. This rapid feedback between theoretical and experimental development shortens the development cycle for new and novel antenna designs using new materials. The Division has a revitalized radar imaging and signal processing facility utilizing multicore PCs running both Linux and Windows operating systems. The Division supports operational systems by developing algorithms for synthetic aperture radar (SAR) and inverse SAR (ISAR) imaging and detection of difficult targets in harsh clutter environments. Software is available for real-time playback of ISAR data and offline processing of SAR data stored on RAID systems with a current online capacity of 96 TB. The systems are connected by a high-speed network. Data is obtained from sponsors or collected using a number of fleet assets, to include the AN/APS-153(V)5.

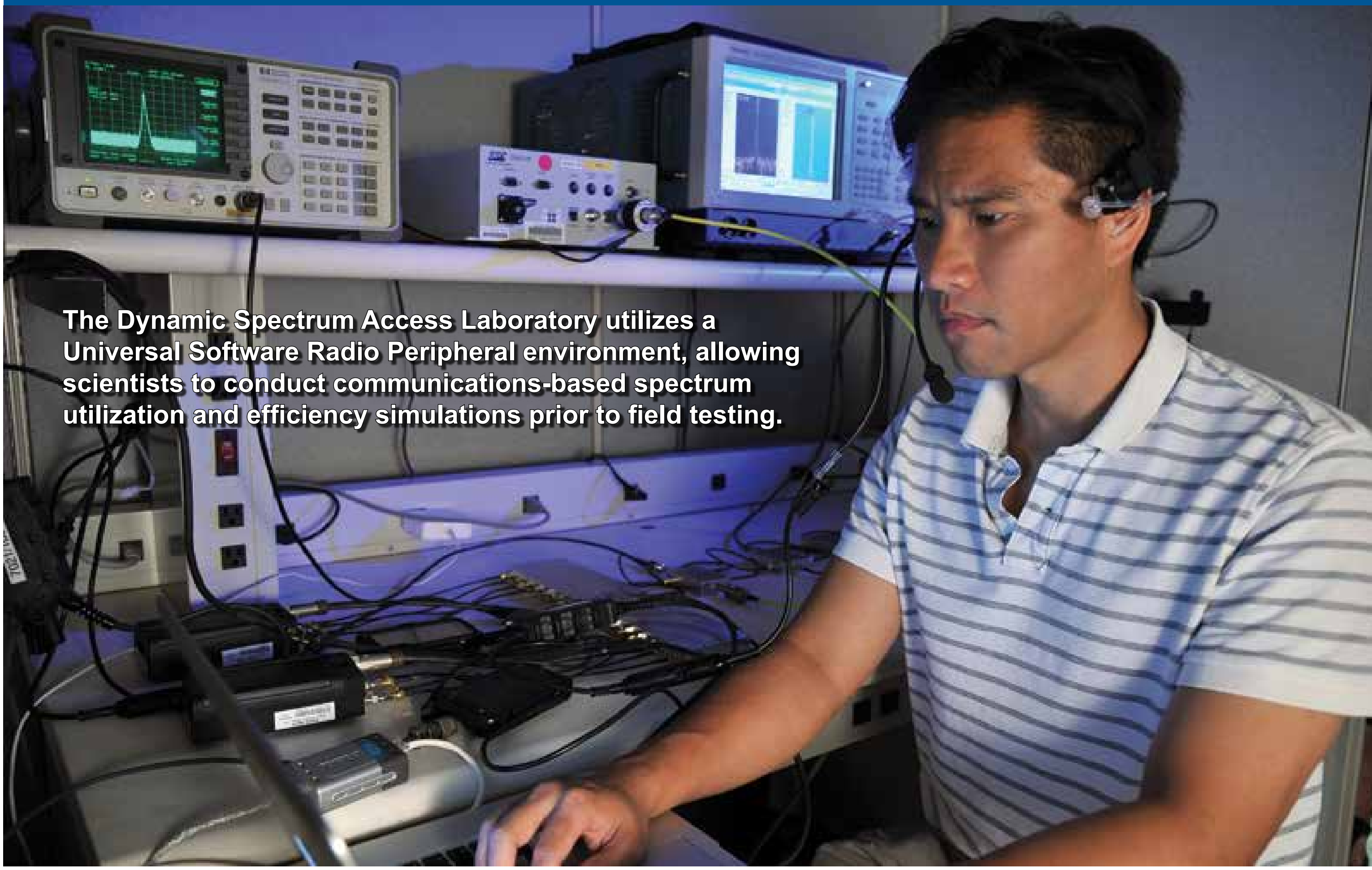
In support of ship-based radar applications, the Division operates the Radar Test Facility at the Chesapeake Bay Detachment (CBD) near Chesapeake Beach, Maryland. The site has the AN/SPS-49A(V)1 long-range air search radar that is used to support R&D as well as fleet initiatives. The radar has been instrumented with a "sidecar" signal processor that supports the development and evaluation of new signal processing concepts. A new asset is the S-Band Waveform Development Testbed. This system operates with up to a 400 MHz instantaneous bandwidth using arbitrary waveforms and can be used for investigating advanced waveforms and signal processing for clutter and interference mitigation. With a 43 dB gain monopulse antenna, the system can collect data from representative targets at operationally relevant ranges.

The Multifunction Radio Frequency (MRF) test bed at CBD is a Systems Directorate installation operated by the Radar Division, with extensive collaboration and contributions from other NRL divisions and industry partners. The facility was originally established as the test bed for the Advanced Multifunction Radio Frequency Concept (AMRFC) prototype. It was subsequently modified to add the Multifunction Electronic Warfare (MFEW) Advanced Development Model (ADM), and most recently expanded to incorporate several Integrated Topside (InTop) and Electromagnetic Maneuver Warfare Command & Control (EMC2) prototypes now in development. The goal of these Office of Naval Research (ONR) sponsored programs is to demonstrate the integration of multiple shipboard RF functions, including radar, electronic warfare (EW), information operations (IO), communications (Comms), and other legacy and newly developed RF capabilities by utilizing a common pool of resources including broadband array antennas, signal and data processing, and signal generation and display hardware controlled by standardized resource allocation management software. The test bed operates over a very wide range of frequencies. The MRF facility consists of interconnected shipping containers modified to house the various multifunction systems and support their associated arrays; a central operator control space; dedicated power and cooling facilities; cabling and system interconnect infrastructure; and administrative, maintenance, and security spaces. The array faces are mounted on pallets at a 15° tilt-back to emulate shipboard installation, and overlook the Chesapeake Bay, facing east in the direction of the Tilghman Island test range on the Maryland Eastern Shore. Presently installed systems include the original AMRFC test bed, and the MFEW and InTop EW/IO/Comm ADMs. New InTop prototypes in development include the Flexible Distributed Array Radar (FlexDAR), the Submarine Satellite Communications ADM, and the Low-Band RF Intelligent Distribution Resource (LowRIDR) multifunction/multiband prototype. Space, power, and cooling have been designed and reserved for these systems along with additional capacity for future EMC2 MRF developments.

The Division originated the concept of high frequency over-the-horizon radar and continues to make significant contributions to the field today. It has access to the Navy's AN/TPS-71 Relocatable Over-the-Horizon Radar (ROTHR) and in addition to providing direct technical support for the program, data collected by the radar is used to support improvements to the systems as well as to evaluate new and innovative HF radar concepts. The Division has recently developed a relocatable high frequency surface wave radar that is used to explore phased array antenna geometries and associated beamforming concepts.

S-Band Waveform Development Testbed.

Information Technology



The Dynamic Spectrum Access Laboratory utilizes a Universal Software Radio Peripheral environment, allowing scientists to conduct communications-based spectrum utilization and efficiency simulations prior to field testing.

NRL's Information Technology Division (ITD) conducts basic research, exploratory development, and advanced technology demonstrations in the collection, transmission, processing, dissemination, and presentation of information. ITD's research program spans the areas of artificial intelligence (AI), autonomous systems, high assurance systems, tactical and strategic computer networks, large data systems, modeling and simulation, virtual and augmented reality, visual analytics, human/computer interaction, communication systems, transmission technology, and high performance computing.

NRL's RF Communications Laboratory conducts research in satellite communications systems and modulation techniques, develops advanced systems for line-of-sight communications links, and conducts designs for the next generation of airborne relays. A Voice Communication Laboratory supports the development of tactical voice technology; a Mobile Network Modeling Laboratory supports modeling, emulation, development, and scenario-based performance evaluation of both tactical network and Mobile Ad Hoc Networking (MANET) capabilities; and a Dynamic Spectrum Allocation/Cognitive Radio Technology Test Lab provides the capability to analyze, test, and develop dynamic, cognitive, networked tactical wireless communications capabilities that efficiently share and exploit the spectrum. A Freespace Laser Communications Laboratory supports the design and development of prototype technical solutions for Naval laser communications requirements.

The Center for Computational Science (CCS) hosts the high performance computing (HPC) and communications efforts at NRL. CCS participates in the DoD HPC Affiliated Research Center (ARC) program providing supercomputer research access to NRL and DoD customers. For high-performance networking, the Center runs the Advanced Technology Demonstration Network (ATDnet) in the Washington, D.C., metro area that provides dark fiber access to research partners. Other research supports high-speed connections (tens to hundreds of Gbps). Current efforts range from mapping traditional large shared memory (SHMEM) problems onto scalar computing systems to emerging cloud architectures to extremely large storage (petabytes and beyond).

CCS provides a full range of IT infrastructure to support NRL-wide needs including web application development and system support along with equipment that supports a cable TV plant, SIPRNet, backbone fiber based network, services and external connectivity to the Defense Research and Engineering Network (DREN). DREN is a high-bandwidth wide area network that provides the communications path within the HPC community, to DoD networks and to the Internet. A current research effort includes Openflow between multiple DREN sites, including NRL.

The Autonomous Systems and Robotics Laboratory provides the ability to develop and evaluate intelligent software, hardware, sensors, and interfaces for human interaction with autonomous systems. The lab includes a number of ground and air platforms, as well as equipment for evaluating interfaces, including eye trackers. A variety of passive and active sensors support research in perception for autonomous systems. The Audio Laboratory combines a state-of-the-art 3D sound environment and multitask test bed for basic and applied human performance studies and Navy information display research. The core of the new Visual Analytics Laboratory is a display wall composed of LCD tiles, which enable teams of analysts to explore massive, diverse streams of data, supporting research into the science of analytical reasoning facilitated by visual interfaces. The Service Oriented Architecture Laboratory is used to investigate, prototype, and evaluate flexible, loosely coupled Web services that can be rapidly combined to meet dynamically changing warfighter needs. The Behavioral Detection Laboratory features a 50-node Cloud cluster to support the development of algorithms, processes, and sensor suites associated with behavioral indicators of deception.

Octavia, one of three anthropomorphic robots at the Navy Center for Applied Research in Artificial Intelligence, uses and understands gestures in order to communicate in high noise environments.

The Configurable Synthetic Merged Environments (CSME, or Sesame) Laboratory enables the assessment of Naval systems, individuals, and teams using virtual prototyping techniques to simulate future warfighting scenarios within surface, undersea, land (including man-portable wearable gear), and air domains. Individuals and teams are able to interact with each other and synthetic entities in a realistic manner to improve training effectiveness. The CSME Laboratory is a complement to the Department of Navy's warfighter performance portfolio.

The Navy Cyber Defense Research Laboratory (NCDRL) provides a valuable resource for research and development (R&D) into the broad spectrum of Cyber, including Information Assurance (IA) and Computer Network Defense (CND). R&D activities include network security systems engineering, malicious code analysis, penetration testing, and reverse engineering.

The Navy Cyber Defense Research Laboratory (NCDRL) reconfigurable infrastructure.

Collectively, NCDRL aims to equip the cyber-warrior at the front lines of defending the network with the tools and capabilities needed to accomplish their mission, while augmenting the information security posture of the Navy and DoD.

NCDRL provides researchers access to a full range of computing infrastructure which include general purpose reconfigurable hardware, virtualization technologies, traffic generation and emulation test beds, deep packet inspection platforms, network intrusion detection/prevention systems, continuous monitoring, and sandbox instrumentation platforms. The environment is robust enough to support testing of a wide array of developmental security technologies as well as USN/DoD IA initiatives (COTS/GOTS) which are vigorously assessed prior to production deployments.

Optical Sciences

Advanced Thin Films Laboratory

The Optical Sciences Division has a broad program of basic and applied research in optics and electro-optics. Areas of concentration include fiber-optic sensing, development of optical materials and sensors for the visible and infrared (IR) spectral regions, integrated optical devices, signal processing, optical communications, panchromatic and hyperspectral imaging for surveillance and reconnaissance, and laser development. Collectively, these technologies form the core of advanced data gathering and communications equipment, designed to aid both the Fleet and the larger Department of Defense community.

To maintain its technical edge in these areas, Optical Sciences maintains a variety of advanced facilities and equipment for manufacturing, testing, and characterizing optical devices and systems.

The Advanced Thin Films Laboratory is a world-class facility for the growth and characterization of optical thin films. The primary deposition system is a cluster tool consisting of interconnected high vacuum chambers, allowing complex, heterogeneous, multilayer films to be deposited without breaking vacuum during processing. The system includes a glove box, sample distribution robot, sputtering chambers for chalcogenide materials and oxides, evaporators for metals and dielectrics, an ultrahigh vacuum optical characterization chamber, an atomic layer deposition chamber with oxide and sulfide capability, and a mask changing module to enable layers to be patterned in situ, eliminating interfacial defects that result from exposure to air.

Other deposition tools within the Advanced Thin Films Laboratory include a stand-alone thermal evaporator for the deposition of IR-transparent chalcogenide glasses, a stand-alone sputterer, and a custom system for deposition on optical fiber. The laboratory also contains a suite of optical, electronic, and thin film characterization equipment. Upgrades are currently underway to install a plasma-enhanced metal-organic chemical vapor deposition system and expanded wet synthesis capability.

The Ultrashort Laser Facility permits experiments to measure the optical nonlinear response of different materials to ultrashort laser pulses. The information learned from such experiments helps in the development of materials that can be used for optical telecommunications, for the protection of sensors and human eyes from hostile laser irradiation, and for the development of new active laser sources.

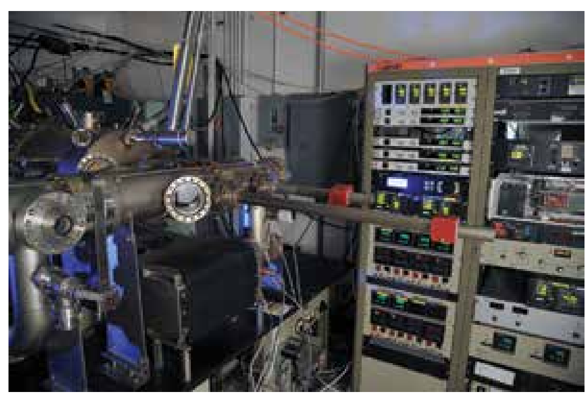
Other recently added facilities include the Optical Fiber Preform Fabrication Facility for making doped and undoped, multimode, single-mode, multicore, and photonic crystal glass preforms at temperatures as high as 2300 °C; the Surface Characterization Facility for ultraviolet and X-ray photoemission spectroscopy, atomic force and scanning tunneling microscopy (STM), and STM-induced light emission measurements; and the molecular beam epitaxial growth system dedicated to infrared lasers and detectors based on GaSb/InAs/AlSb quantum well and superlattice structures.

In addition, an extensive set of laboratories exists to develop and test new laser and nonlinear frequency conversion concepts and to evaluate nondestructive test and evaluation techniques. Fiber-optic sensor testing stations include acoustic test cells and a three-axis magnetic sensor test cell. There is also an Ultralow-loss Infrared Fiber-Optic Waveguide Facility using high-temperature IR glass technology. The facilities for ceramic optical materials include powder preparation, vacuum presses, and a 50-ton hot press for sintering.

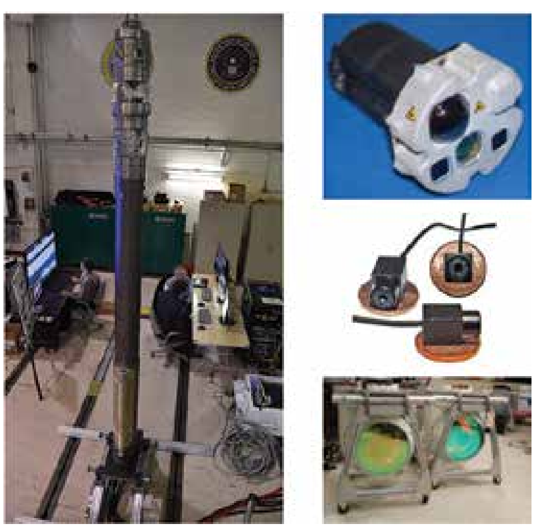
The Focal Plane Array Evaluation Facility allows measurement of the optical and electrical characteristics of infrared focal plane arrays being developed for advanced Navy sensors. The IR Missile-Seeker Evaluation Facility performs open-loop measurements of the susceptibilities of IR tracking sensors to optical countermeasures. An ultra-high-vacuum multichamber deposition apparatus is used for fabrication of electro-optical devices and can be interlocked with the Surface Characterization Facility.

The Advanced Optical Materials Fabrication Laboratory.

Scientists work on the alignment of an experiment designed to quantify material response to ultrashort laser pulses.



Molecular beam epitaxy (MBE) system dedicated to quantum confined GaSb/InAs/AlSb structures for midwave infrared laser development.



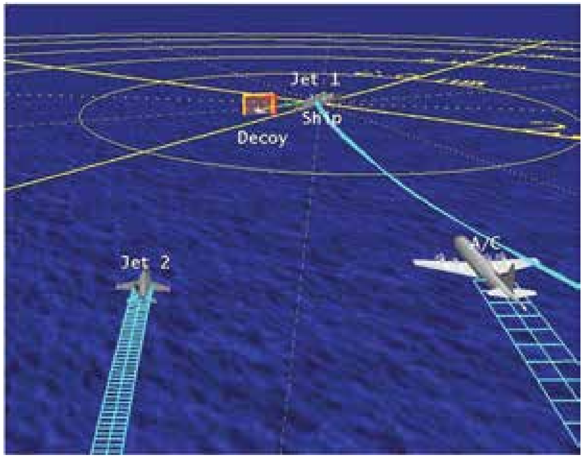
The Optical Sciences Division develops and fields numerous electro-optical/infrared systems. Clockwise from left: 360-degree panoramic periscope for *Virginia*-class submarines; Distributed Aperture Infrared Countermeasure (DAIRCM); advanced hyperspectral imaging systems ranging from extremely small (ounces) to large, long-range cameras (>100 lb).

Tactical Electronic Warfare

Learjet with simulators during RIMPAC exercises.

The Tactical Electronic Warfare (TEW) Division's program for electronic warfare (EW) research and development covers the entire electromagnetic spectrum. The program includes technology research and advanced developments and their applicability to producing EW products for the Fleet. The range of ongoing activities includes components, techniques, and subsystems development as well as system conceptualization, design, and EW effectiveness evaluation. The focus of the research activities extends across the entire breadth of the battlespace. These activities emphasize providing the methods and means to detect and counter enemy hostile actions via threat neutralization — from the beginning, when enemy forces are being mobilized for an attack, through to the final stages of the engagement. In conducting this program, the TEW Division employs an extensive array of special research and development laboratories, anechoic chambers, and modern computer systems used for modeling and simulation. Dedicated field sites and airborne platforms allow for the conduct of field experiments and operational trials. This combination of scientists, engineers, and specialized facilities also supports the innovative use of all Fleet defensive and offensive EW assets currently available to operational forces.

Radio Frequency Countermeasures anechoic chamber for EW testing.

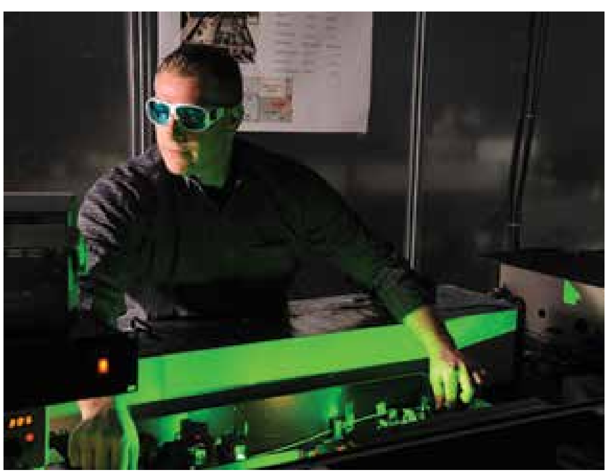


TEWD develops and implements advanced visualization tools to support EW systems development and analysis.

The Central Target Simulation Facility is a high-performance, hardware-in-the-loop simulator for real-time closed-loop testing and evaluation of electronic warfare systems and techniques to counter the antiship missile threats.

EATES — Electronic Attack Technique Evaluation System, a stand-alone portable EA testing system.

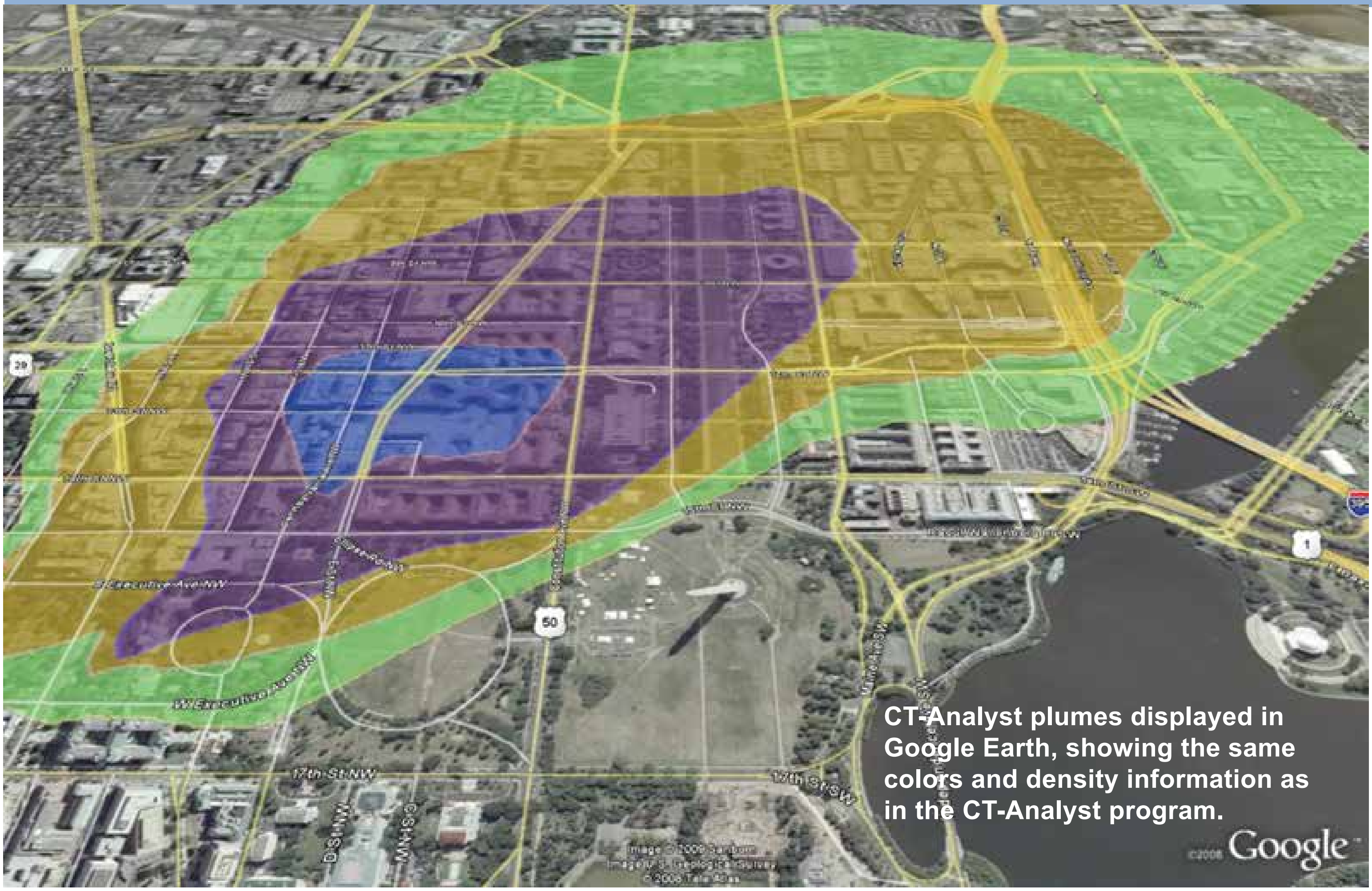
TEWD engineers prepare for dynamic testing of the 4000 lb Roll-Pitch Stabilized Antenna System mounted on NRL's Ship Motion Simulator located at the Chesapeake Bay Detachment facility.



NRL research physicist aligning the TEWD 30 TW Ti:Sapphire laser system.

XFC prototype in flight under fuel cell power.

Laboratories for Computational Physics and Fluid Dynamics



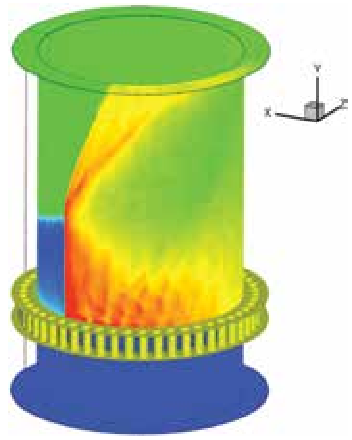
CT-Analyst plumes displayed in Google Earth, showing the same colors and density information as in the CT-Analyst program.

The Laboratories for Computational Physics and Fluid Dynamics (LCP&FD) is staffed by physicists, engineers, and computer scientists who develop software and use high-performance computers to solve priority problems for the Navy, the Department of Defense, and the nation when existing capabilities and available commercial software prove inadequate to the application. For example, the LCP&FD developed the CT-Analyst crisis management software (figure above) so that first responders can have instant predictions of an airborne contaminant spread in an urban environment.

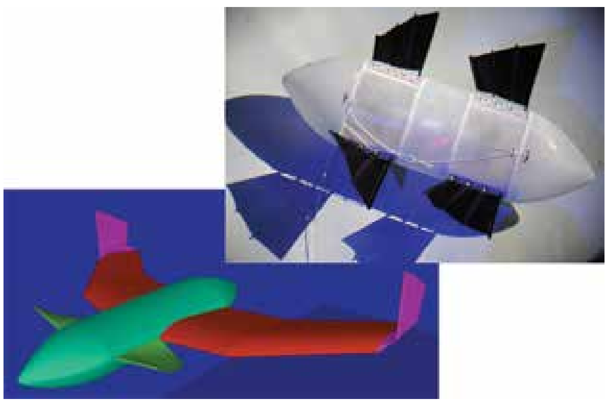
The LCP&FD maintains a very powerful collection of computer systems applied to a broad collection of work. There are currently 3296 clustered x86_64 cores and their associated support systems. In addition there are over 40 Apple workstations in the group, most of which are capable of large calculations both independently and in parallel ad hoc clusters.

There are five 64-bit x86 multicore distributed memory clusters, each well coupled with Infiniband high-speed switched interconnect. Three of the clusters contain manycore coprocessors. The newest system consists of 136 Intel Xeon Phi coprocessors. The second consists of 16 NVIDIA Maxwell class GPUs and 70 Intel Xeon Phi coprocessors. The third system is comprised of 88 NVIDIA Fermi class GPUs. All of the manycore processors are tightly coupled to their associated x86_64 multicore processor nodes. A Scale MP based shared memory machine is available for large memory processing.

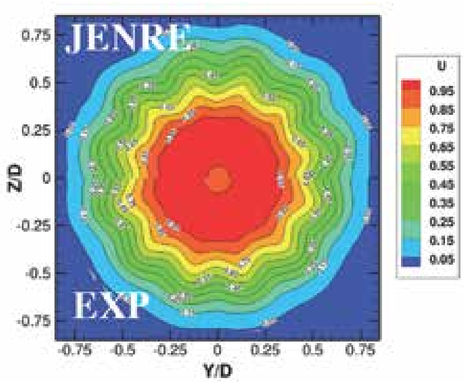
All systems share 250 terabytes of storage for use during a simulation and at least one gigabyte of memory per processor core. All unclassified systems share a common disk space for home directories as well as 3 terabytes of AFS space.



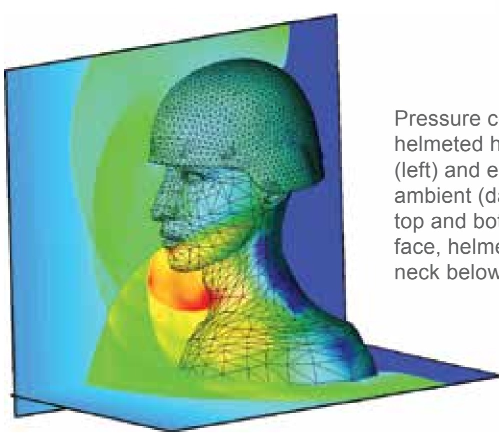
The computed flow field inside a rotating detonation engine with mixture plenum (bottom), injector plate and injectors (center), and combustion chamber (top). This new class of engines has been investigated computationally and been shown to have the potential to reduce fuel consumption by 25% while providing the same performance as current gas-turbine engines.



Development of bio-inspired unmanned underwater vehicle (UUV) propulsion and control mechanisms is accomplished using unsteady three-dimensional computational fluid dynamics (CFD) tools. These designs and the subsequent construction of the bio-robotic mechanisms are expanding the envelope of unmanned air and sea vehicle performance.

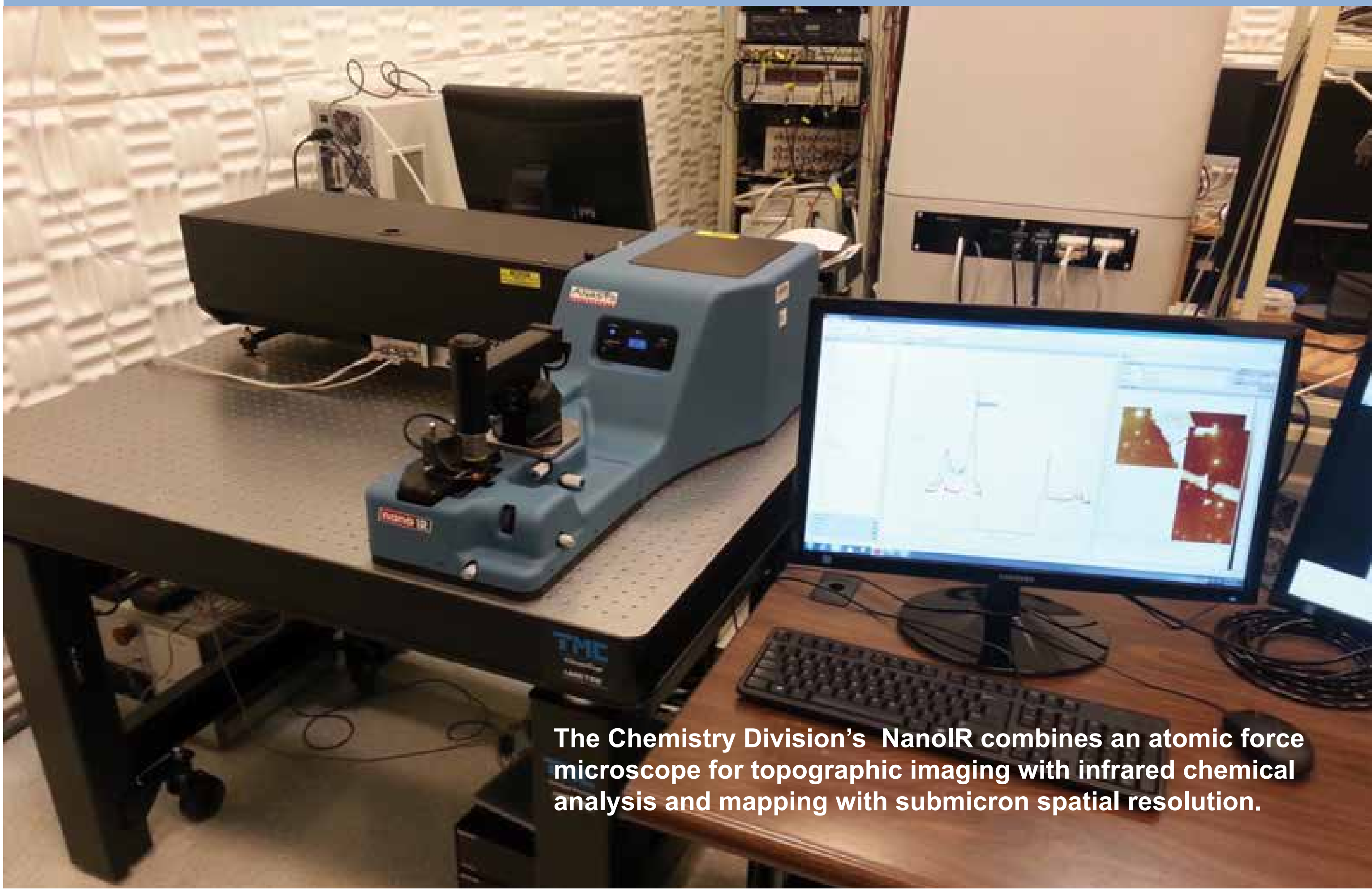


Simulations using the NRL developed JENRE code show that it predicts supersonic jet flow features and noise very accurately. Here the computed (top half of picture) cross-sectional jet velocity is compared to the experimentally measured data (bottom half).



Pressure contours resulting from blast interaction with a helmeted head. The shock wave approaches from the front (left) and envelopes the geometry; the boundary between ambient (dark blue) and post-shock (green) air is seen at the top and bottom right. Interacting shock reflections from the face, helmet, and torso generate high pressures (red) on the neck below the chin.

Chemistry



The Chemistry Division's NanoIR combines an atomic force microscope for topographic imaging with infrared chemical analysis and mapping with submicron spatial resolution.

NRL has been a major center for chemical research in support of naval operational requirements since the late 1920s. The Chemistry Division continues this tradition. The Chemistry Division conducts basic research, applied research, and development studies in the broad fields of diagnostics, dynamics, synthesis, materials, surface/interfaces, environment, corrosion, combustion, and fuels. Specialized programs currently within these fields include the synthesis and characterization of organic and inorganic materials, coatings, composites, nondestructive evaluation, surface/interface modification and characterization, nanometer structure science/technology, chemical vapor processing, tribology, solution and electrochemistry, mechanisms and kinetics of chemical processes, analytical chemistry, theoretical chemistry, decoy materials, radar-absorbing materials/radar-absorbing structures (RAM/RAS) technology, chemical/biological warfare defense, atmosphere analysis and control, environmental remediation and protection, corrosion science and engineering, marine coatings, personnel protection, and safety and survivability. The Division has several research facilities.

Chemical analysis facilities include a wide range of modern photonic, phononic, magnetic, electronic, and ionic-based spectroscopic/microscopic techniques for bulk and surface analysis.

The Magnetic Resonance Facility includes advanced high-resolution solid-state nuclear magnetic resonance (NMR) spectroscopy techniques to observe nuclei across much of the periodic table and provides detailed structural and dynamical information.

The Nanometer Characterization/Manipulation Facility includes fabrication and characterization capability based on scanning tunneling microscopy/spectroscopy, atomic force microscopy, and related techniques.

The Materials Synthesis/Property Measurement Facility has special emphasis on polymers, surface-film processing, and directed self-assembly.

The Chemical Vapor and Plasma Deposition Facility is designed to study and fabricate materials such as diamond using in situ diagnostics, laser machining, and plasma deposition reactors.

The Navy Fuel Research Facility performs basic and applied research to understand the underlying chemistry that impacts the use, handling, and storage of current and future Navy mobility fuels.

Fire research facilities include a 11,400 ft^3 fire research chamber (Fire I) and the 457 ft ex–USS *Shadwell* (LSD 15) advanced fire research ship. Commensurate support has been devoted to survivability of the new classes of ships, DDX, LPD 17, LCS, CVNX, and LHA(R).

The Marine Corrosion and Coatings Facility located on Fleming Key at Key West, Florida, offers a “blue” ocean environment and unpolluted, flowing seawater for studies of environmental effects on materials. Equipment is available for experiments involving accelerated corrosion and weathering, general corrosion, long-term immersion and alternate immersion, fouling, electrochemical phenomena, coatings application and characterization, cathodic protection design, ballast water treatment, marine biology, and corrosion monitoring.

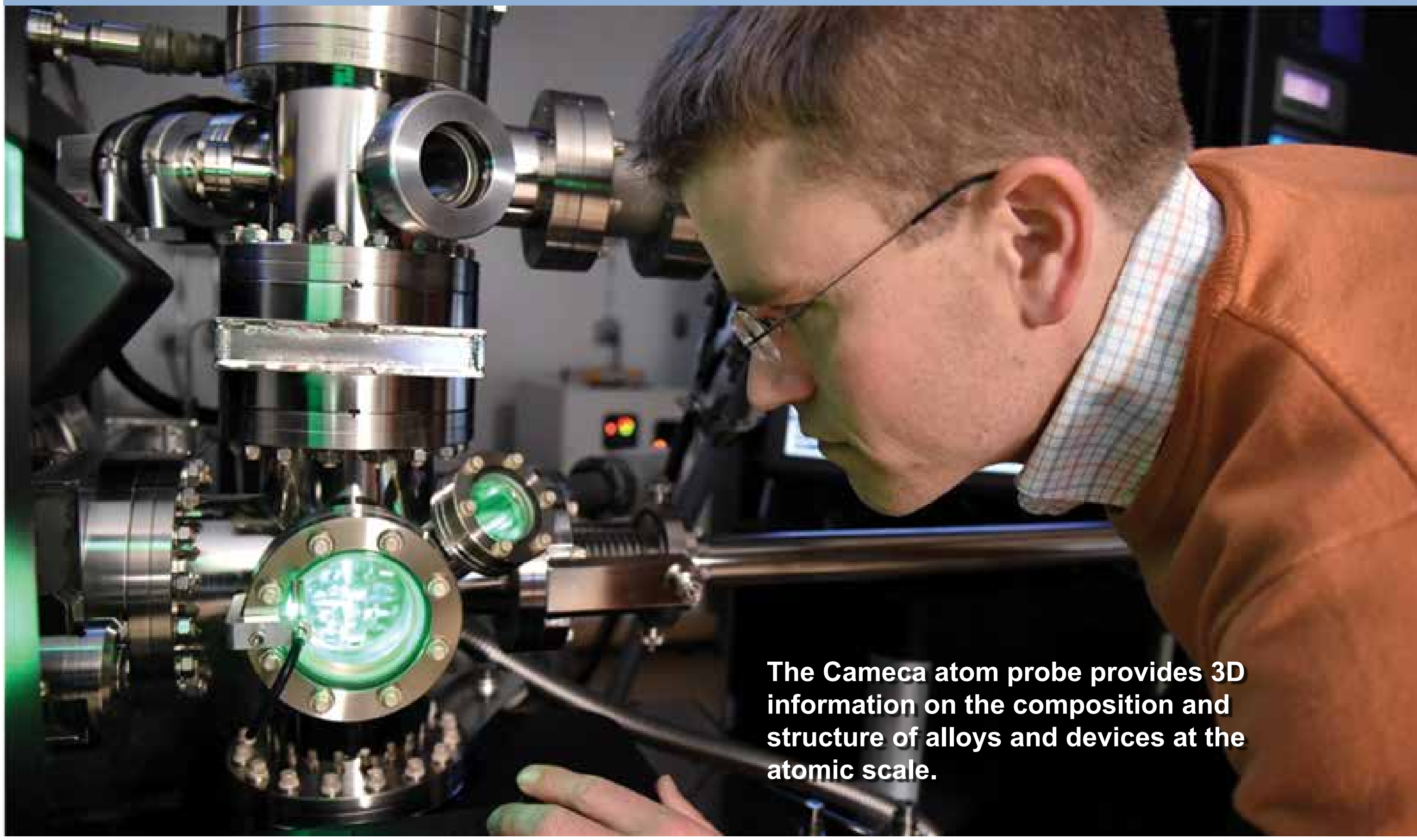
The Chemistry Division has focused on force protection/homeland defense (FP/HD) since September 11, 2001, especially on the development of improved detection techniques for chemical, biological, and explosive threats. As part of a multidivisional program to develop new technology systems, the Chemistry Division is a major contributor to the NRL Institute for Nanoscience. Nanoscience complements FP/HD in that nanoscience is expected to provide dramatic improvements to chemical/biological detection, protection, and neutralization. Chemistry will approach the nanoscale from the bottom up — building smaller atoms and molecules into nanostructures with new properties and developing the directed assembly of nanostructures into hierarchical systems. The NRL Nanoscience building is linked directly into the Chemistry building to provide controlled access and auxiliary space for work not requiring a “low noise” environment.

The Thermo Scientific LTQ Orbitrap XL high-resolution mass spectrometer is equipped with electrospray ionization, atmospheric-pressure chemical ionization, and a flowing atmosphere ambient ionization source for high speed analysis of complex samples and development of new ambient detection capabilities. The instrument provides mass resolution in excess of 100,000 with a mass accuracy of <5 ppm and can perform sophisticated multistage fragmentation experiments for elucidation of molecular structure.

The Micro-Raman system is a multiwavelength, fully automated spectrometer providing chemical microprobe analysis and mapping of organic, inorganic, and biological specimens.

The Leica UC7/FC ultramicrotome with cryo attachment can efficiently section materials for further study, and is capable of ultra-thin sections in the 50 nm range.

Material Science and Technology



The Cameca atom probe provides 3D information on the composition and structure of alloys and devices at the atomic scale.

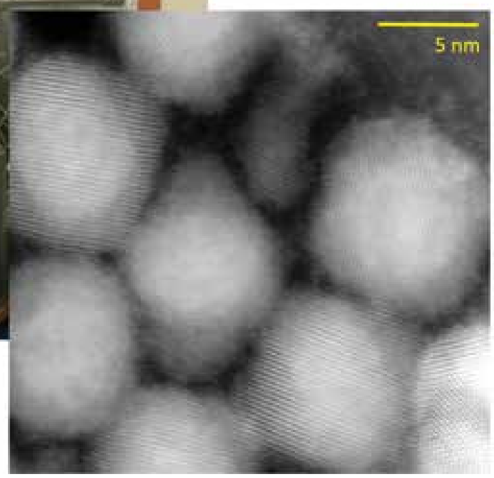
The Materials Science and Technology Division (MSTD) at NRL provides expertise and facilities to foster a broad range of materials innovation. The Division houses many specialized and unique facilities for carrying out basic and applied materials modeling, synthesis, and characterization research.

Electronic structure and multiphysics modeling is performed in The Center for Computational Materials Science, which operates several high performance computing clusters that complement the resources of the DoD Supercomputing Resource Centers. These hardware resources are used to run in-house custom-developed and externally custom-developed codes (VASP, LAMMPS, ALE3D, CUBIT, AERO-suite) and commercial codes (COMSOL, ANSYS, ABAQUS, etc.) for understanding fundamental materials properties.

In 2015, MSTD added a new 3D X-ray Computed Microtomography facility built on a Zeiss Xradia 520 Versa X-ray microscope. This system allows for in situ measurement of component geometry and material microstructure under different loading conditions of strain and temperature. This system is unique in its capability for diffraction contrast tomography (DCT) that has only been previously available on synchrotron beamlines. DCT provides nondestructive, high-resolution grain maps for polycrystalline samples. The system is useful for characterization of a wide range of materials including additive-manufactured materials, batteries, fuel cells, joined materials, composites, and corrosion products, as well as hard and soft biological materials and imaging of subcellular to cellular features with submicron resolution.

The Electrical, Magnetic, and Optical Measurement Facility contains instruments for fundamental studies of the magnetic, electrical, optical, and thermal properties of materials and devices. Magnetometry and magnetotransport measurements are performed within a Quantum Design MPMS SQUID magnetometer (± 5T; 1.7–400 K) and PPMS system (±9 T; 1.7–400 K) and a Microsense LLC vibrating sample magnetometer (± 2 T; 90–800 K). MSTD has added new capabilities in the measurement and characterization of artificial multi-ferroic materials.

The Bulk Materials Fabrication Facility provides equipment for fabrication and processing, including arc-melting and furnace casting for conventional metallic alloys, a single crystal growth furnace, and rapid solidification by splat quenching or melt spinning. Ceramic and ceramic-matrix composites processing facilities include conventional, controlled atmospheric furnaces,



Dark field scanning transmission electron microscopy image revealing the atomic-scale core-shell structure of PbTe/PbS nanoparticles.

hot presses, milling facilities, tape casting, particle, and sol-gel and organometallic coating processing capabilities.

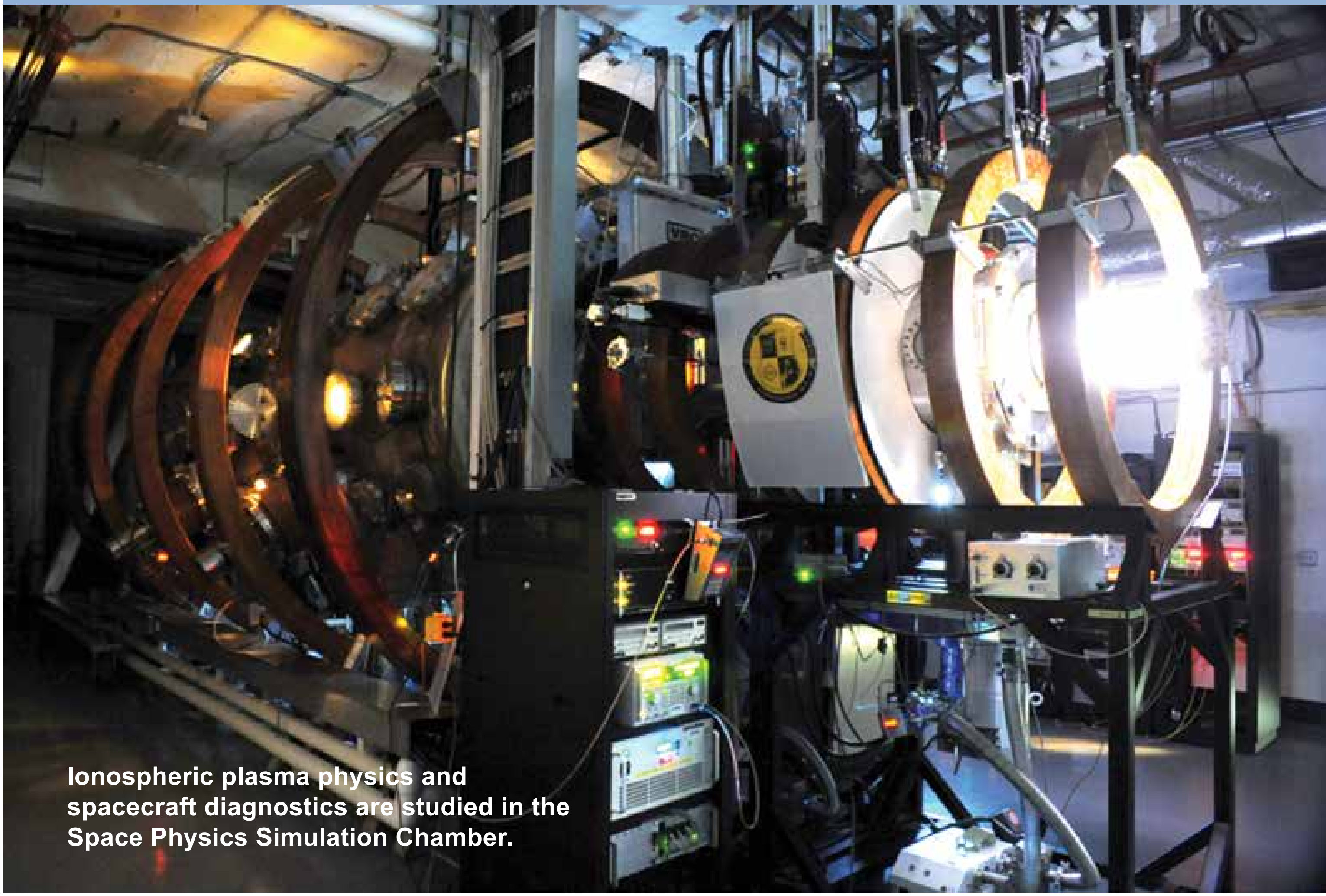
The Thin-Film Materials Synthesis and Processing Facility provides users a variety of techniques for growth and processing of thin films (thickness 1 µm or less). Sputter deposition is a versatile method of depositing metallic and dielectric films and several tools are available for growth on samples up to 8 inches in diameter and at room and elevated temperature, or growth in magnetic field. Thermal evaporation of metals is implemented in both high-vacuum and ultra-high-vacuum systems with surface science tools for analysis. Pulsed laser deposition with variable stage temperature and controlled atmosphere is the preferred method for growth of oxides. Laser direct-write ablation and deposition processes provide unique methods for imposing CAD-defined features to a substrate.

The Materials Science and Technology Division's Accelerator Mass Spectrometry Facility provides positive ion analysis of materials for trace chemical and isotope composition.

The Micro/Nanostructure Characterization Facility contains equipment for imaging of materials from the macro-scale down to the atomic scale. This facility includes a JSM-7001F variable pressure scanning electron microscope (SEM), an FEI Tecnai G2 30 analytical scanning transmission electron microscope (STEM), a JEOL 2200FS field-emission analytical STEM, and a new Nion aberration-corrected STEM with 80 picometer resolution. These electron microscopes have capabilities for energy dispersive X-ray spectroscopy, electron energy loss spectroscopy, Z-contrast imaging, spectral compositional mapping, and electron backscatter diffraction. This facility also includes a new robotic serial sectioning system (RS3D) for automatically removing small amounts of material and then imaging the structure, crystallography, and/or chemistry of the exposed surface in an SEM for 3D reconstruction of materials. NRL has also acquired a state-of-the-art Cameca 4000X Si LEAP (local electrode atom probe) to analyze the true 3D structure of materials at atomic resolution with chemical sensitivity approaching 10 atomic parts per million.

The Accelerator Mass Spectrometry Facility at NRL is currently equipped with a single stage accelerator mass spectrometer (SSAMS) that is capable of analyzing positive ions, making the NRL SSAMS facility globally unique, as all other AMS facilities accept only negative ions, and opening up analysis of positive ions of nearly the entire periodic table. At NRL, the SSAMS is currently coupled to a secondary ion mass spectrometer. The marriage of these two instruments allows for trace isotopic and elemental analyses of solid materials, particles, and films and facilitates spatially resolved analysis of complex materials spanning the range from semiconductors and engineered materials to nuclear and geochemically interesting samples.

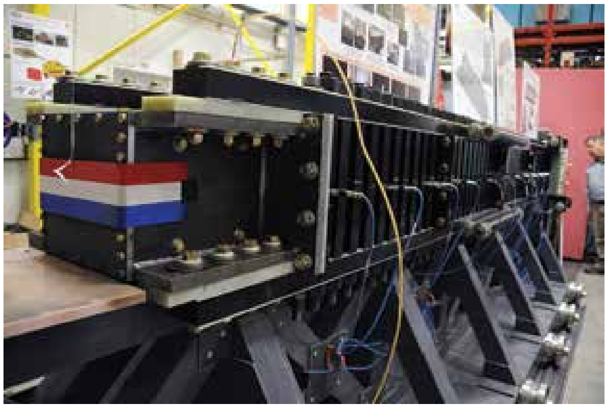
Plasma Physics



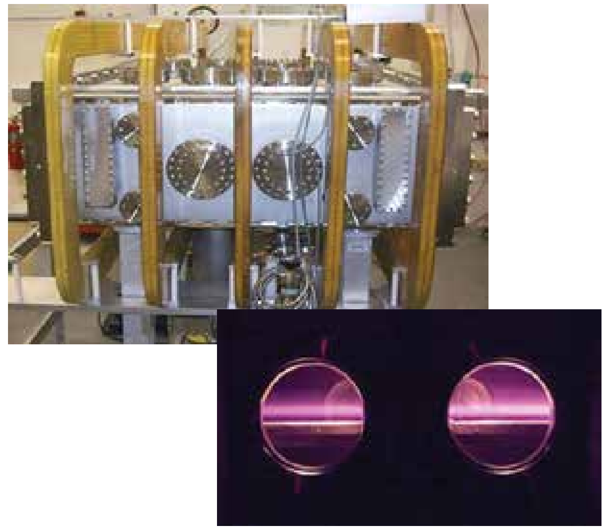
Ionospheric plasma physics and spacecraft diagnostics are studied in the Space Physics Simulation Chamber.

The Plasma Physics Division conducts basic and applied research in space plasmas; inertial confinement fusion (ICF); ultra-short-pulse laser interactions; directed energy; railguns; pulsed-power and intense particle beams; materials processing; advanced diagnostics; radiation-atomic physics; and nonlinear dynamics.

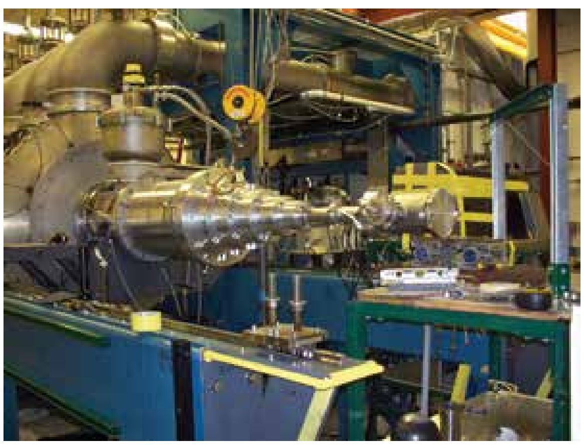
The Space Physics Simulation Chamber generates near-Earth plasma environments for studying space plasma phenomena and spacecraft diagnostic development and testing. Nike and Electra are major KrF laser facilities for ICF research, studying ICF target physics and developing repetitively pulsed KrF technologies, respectively. The Ultrashort-Pulse, High-Intensity Laser facility has both a 10 Hz (15 TW) and kilohertz (0.45 TW) Ti:Sapphire laser to investigate laser-driven acceleration and nonlinear laser–plasma interactions. Directed energy research is performed in the High Energy Laser Lab, which has four multikilowatt fiber lasers to study laser propagation, incoherent beam combining, and power beaming. The Materials Testing Facility houses a 6-meter-long railgun used to study the materials issues of electromagnetic launch for the Navy and Department of Defense's multimission railgun program. A new small caliber railgun will fire repetitively and expand our knowledge of materials, pulsed power, and energy storage. The Division has two large, high-voltage, pulsed-power devices, Gamble II and Mercury, which are used to produce intense electron and ion beams, flash X-ray sources, and high-density plasmas for application to nuclear weapons effects testing, radiography, and active detection of nuclear materials. The Division uses both microwaves and plasmas for materials processing applications. The microwave materials processing laboratory includes a 20 kW, CW, 83 GHz gyrotron. The Large Area Plasma Processing System (LAPPS) generates ultra-low-temperature plasmas for studying the modification of energy sensitive materials such as polymers, graphene, and biologicals. Two atmospheric discharge systems are used to study plasma processing and synthesis, plasma biology, and plasma aerodynamics.



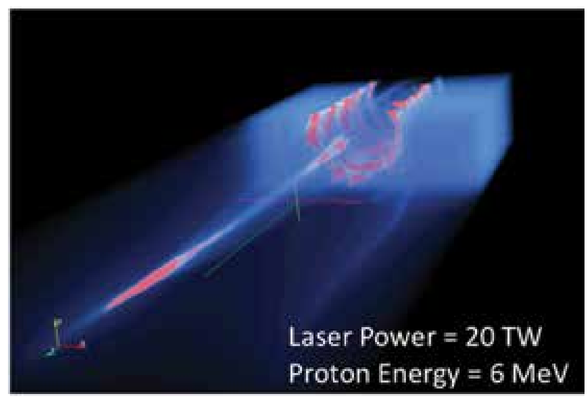
The NRL Small Railgun (SRG) is used for studies of railgun physics at smaller scale and will have a multiple shot capability.



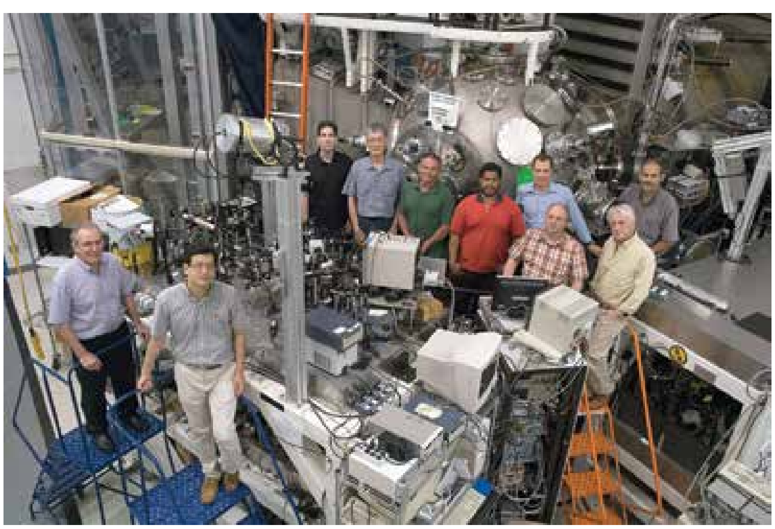
The Large Area Plasma Processing System (LAPPS) is used to develop, characterize, and study plasma-based processing of energy sensitive materials.



Tapered front-end of Mercury accelerator (6 MV, 360 kA, 50 ns) for dual-axis down-hole radiography.



TURBOWAVE simulation of proton acceleration from a hydrogen gas target driven by an ultrashort-pulse laser.



Nike target chamber area and members of the Nike team. The Nike laser is used to study target physics for inertial confinement fusion and various defense applications.

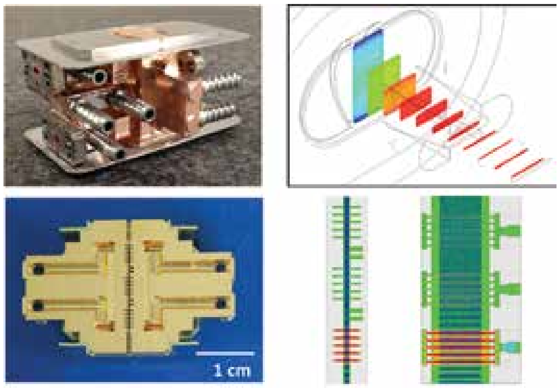
Electronics Science and Technology

The Electronics Science and Technology Division's Advanced Silicon Carbide Epitaxial Research Laboratory (ASCERL).

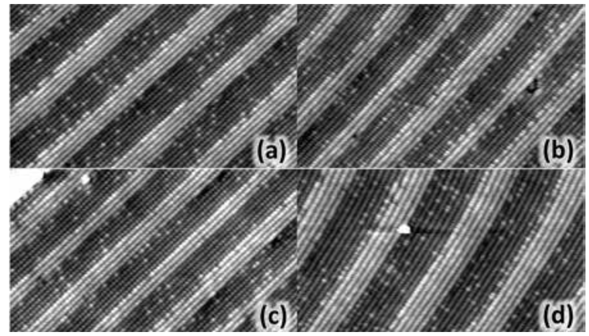
The Electronics Science and Technology Division conducts a multidisciplinary basic and applied research program in solid-state electronics; electronic materials including growth, theory, and characterization of semiconductors and heterostructures; surface and interface science; microwave and millimeter-wave components and techniques; microelectronic device research and fabrication; nanoelectronics science and technologies; vacuum electronics; power electronics; photovoltaics and optoelectronics; and modeling and simulation.

The Division operates 13 major facilities: Ultrafast Laser Facility (ULF), Solar Cell Characterization Laboratory (SCCL), Compound Semiconductor Processing Facility (CSPF), Laboratory for Advanced Materials Synthesis (LAMS), Center for Advanced Materials Epitaxial Growth and Characterization (Epicenter), Electronic Transport Laboratory (ETL), Ultra-Violet Photolithography Laboratory for Submillimeter-Wave Devices (UV-PL), Millimeter-Wave Vacuum Electronics Fabrication Facility (MWVEFF), Advanced Silicon Carbide Epitaxial Research Laboratory (ASCERL), Optoelectronic Scanning Electron Characterization Facility (OSECF), Infrared Materials and Detectors Characterization Laboratory (IR Characterization Lab), Atomic Layer Deposition System (ALD), Atomic Layer Epitaxy System, and High Pressure Multi-Anvil System (HPMAS).

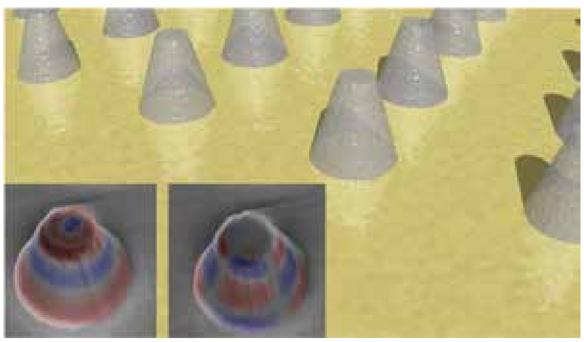
The CSPF processes compound semiconductor structures on a service basis, especially if advanced fabrication equipment such as electron beam lithography for reactive ion etching is required. But most fabrication can be hands-on by NRL scientists to assure personal process control and history. The LAMS uses metallorganic chemical vapor deposition to synthesize a wide range of thin films, particularly wide bandgap semiconductors such as gallium nitride (GaN) and related alloys. The Epicenter (a joint activity of the Electronics Science and Technology, Materials Science and Technology, Optical Sciences, and Chemistry Divisions) is dedicated to the growth of multilayer nanostructures by molecular beam epitaxy (MBE). Current research involves the growth and etching of conventional III-V semiconductors, ferromagnetic semiconductor materials, 6.1 Å III-V semiconductors, and II-VI semiconductors. The structures grown in this facility are analyzed via in situ scanning tunneling microscopy and angle-resolved electron microscopy. The ETL enables comprehensive DC and RF electronic characterization of materials and devices down to cryogenic temperatures and under a variety of magnetic and optical field conditions. The ASCERL is the focal point of NRL efforts to develop thin-film heterostructure materials needed for high-voltage, high-power silicon carbide (SiC) power electronic components in future naval systems. ASCERL uses



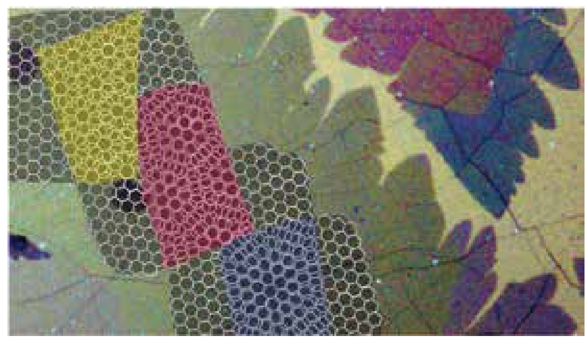
NRL 7.7 kW peak power W-band sheet beam extended interaction klystron circuit, together with device simulations using NRL/Leidos 3D electron gun design code MICHELLE and NRL GPU based 3D PIC code NEPTUNE.



High-resolution, cross-sectional scanning tunneling microscopy images of type-II superlattice structure are shown in (a) and (b), and images of the "W"-structured type-II superlattice are shown in (c) and (d). Bright regions correspond to the (Al)GaInSb layers and the dark regions correspond to the InAs layers.



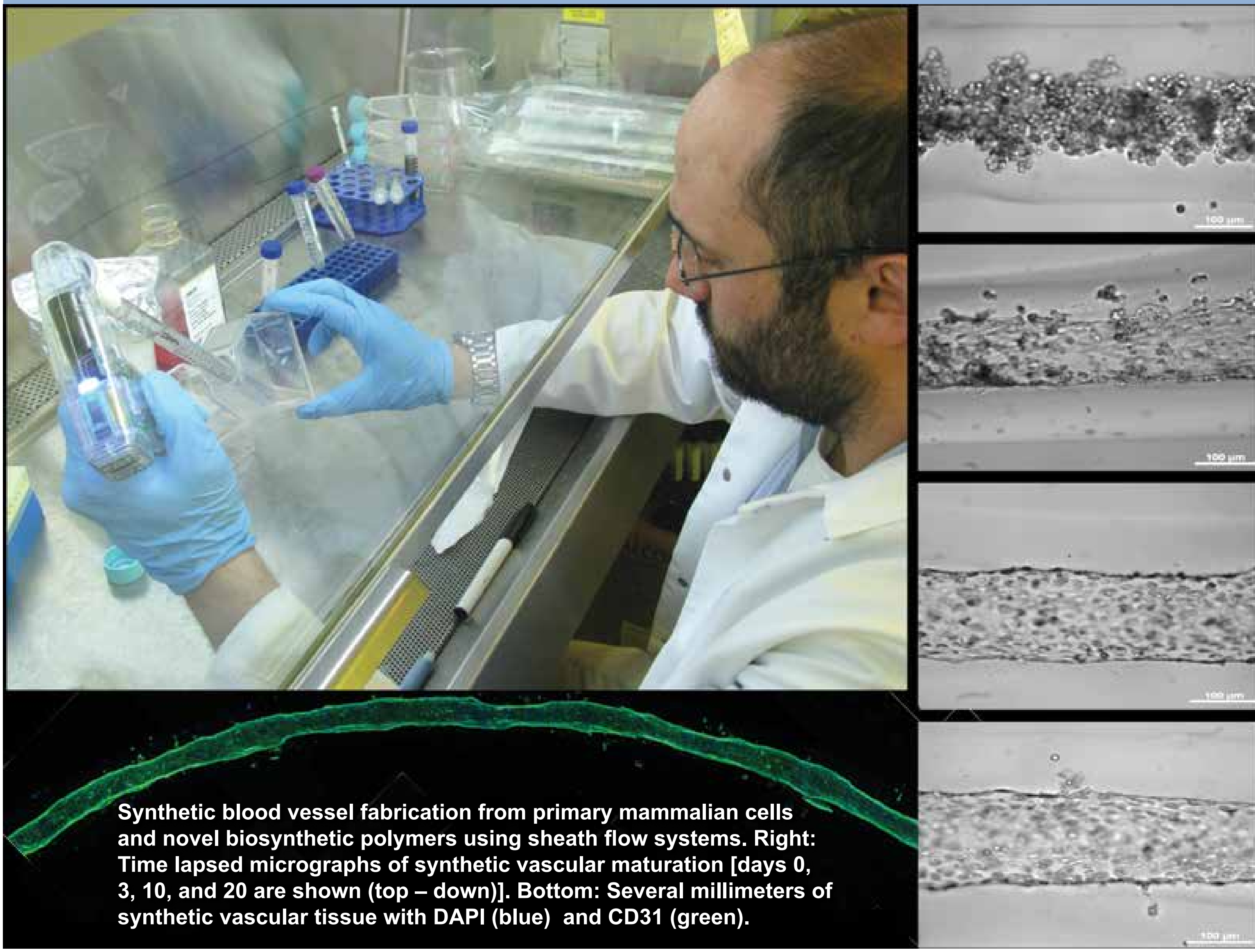
Hexagonal boron nitride, a 2D van der Waals crystal like graphene, is a naturally hyperbolic material, simultaneously exhibiting metallic and dielectric-like optical properties along different crystal axes. Cone-shaped nanostructures (diameter from 100 to 1000 nm) highly confine light, collecting free space wavelengths ranging from 6–7 and 12–13 μm and compressing the photons down to volumes 2 x 10^5 times smaller.



The properties of bilayer graphene films depend on the relative orientation or twist of the two layers. The effect of this angular dependence is that two stacked polycrystalline graphene films have a patchwork of colored regions that appear red, blue, or yellow. This "stained-glass window" appearance arises from the emergence of a narrow absorption band due to direct electronic coupling between the layers.

an EPIGRESS reactor capable of growing thick, low-defect, ultra-high-purity SiC epitaxial layers. The SCCL studies new and emerging solar cell technologies for tactical applications including terrestrial and space environments. The ULF is optimized for the characterization of photophysical and photochemical processes on a timescale of tens of femtoseconds. It includes a synchronously pumped dye laser system for simulating the effects of charge deposited in semiconductors characteristic of space radiation. The UV-PL and MWVEFF are key laboratories for developing precision, all-metal structures for electron optics, electron beam-wave interaction (e.g., amplifiers and oscillators), and passive electromagnetic devices. The UV-PL uses lithographic techniques and chemical electroforming to create high height-to-width aspect ratio structures (up to 10:1) with feature sizes as small as 5 μm. These dimensions are compatible with devices that can produce coherent electromagnetic radiation at submillimeter wavelengths. The MWVEFF contains a computer numerically controlled (CNC) milling machine and a CNC precision lathe capable of fabricating intricate millimeter-wave vacuum electronic components and a wire electric discharge machining (EDM) tool for fabrication of millimeter-wave and submillimeter-wave components that cannot be fabricated by conventional rotary cutting tools. EDM offers a noncontact process for both hard and soft metals as well as SiC and doped silicon.

Center for Bio/Molecular Science and Engineering



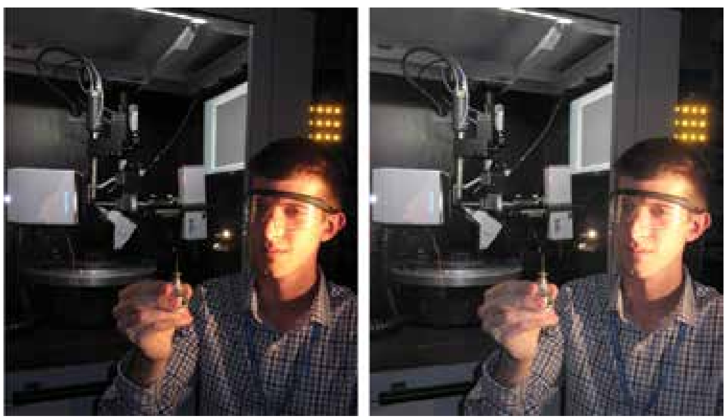
Synthetic blood vessel fabrication from primary mammalian cells and novel biosynthetic polymers using sheath flow systems. Right: Time lapsed micrographs of synthetic vascular maturation [days 0, 3, 10, and 20 are shown (top – down)]. Bottom: Several millimeters of synthetic vascular tissue with DAPI (blue) and CD31 (green).

The Center for Bio/Molecular Science and Engineering conducts cross-disciplinary, bio-inspired research and development to address problems relevant to the Navy and Department of Defense by exploiting biology's well-known ability for developing effective materials and sensing systems. The primary goal is to translate cutting-edge, bio-based discoveries into useful materials, sensors, and prototypes that can be scaled up, are robust, and lead to enhanced capabilities in the field. The challenges include identifying biological approaches with the greatest potential to solve Navy problems and provide new capabilities while focusing on bio-inspired solutions to problems that have not otherwise been solved by conventional means.

Studies involve biomaterial development for chemical/biological warfare defense, structural and functional applications, and environmental quality/cleanup. Program areas include optical biosensors, nanoscale manipulations, genomics and proteomics, bio/molecular and cellular arrays, surface modification, energy harvesting, systems biology, viral particles as scaffolds, and bio-organic materials from self-assembly.

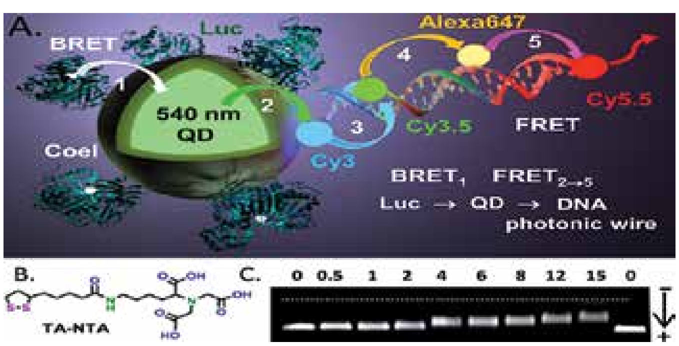
The staff of the Center is an interdisciplinary team with expertise in biochemistry, surface chemistry, biophysics, molecular and cell biology, organic synthesis, materials science, and engineering. The Center also collaborates throughout NRL and with other government laboratories, universities, and industry.

The Center's modern facilities include laboratories for research in chemistry, biochemistry, systems biology, and physics. Specialized areas include controlled-access laboratories for cell culture and molecular biology, an electron microscope facility, a scanning probe microscope laboratory, instrument rooms with access to a variety of spectrophotometers, a multichannel surface plasmon resonance (SPR) sensor, and an optical microscope facility including polarization, fluorescence, and confocal microscopes. Additional laboratories accommodate nuclear magnetic resonance (NMR) spectroscopy, liquid chromatography–mass spectrometry (LCMS), and fabrication of microfluidic and micro-optical systems in polymers. The Center maintains a state-of-the-art X-ray diffraction system including a MicroSTAR-H X-ray generator. In combination with new detectors and components, the system is ideal for data collection on proteins or very small single crystals of organic compounds and is also capable of collecting data on films and powders. Core facilities have been established for fluorescence activated cell sorting (FACS), micro-array analysis, next generation sequencing, circular dichroism spectroscopy, and 3D printing and rapid prototyping. The Center has recently installed an analytical ultracentrifuge to facilitate separation and characterization of proteins and protein complexes. The mass spectrometry (MS) facility was also enlarged to enable small molecule and proteomic analyses of biological, environmental, and clinical samples by offering state-of-the-art instrumentation and proteomics expertise in preparation, analysis, and bioinformatic interpretation of experimental data and manual interpretation of MS/MS spectra.



Sample prepared for X-ray diffraction on the new Bruker D8 Quest that features a state-of-the-art CMOS based detector and a micro-source that operates at only 50 watts but produces an X-ray intensity on the sample close to that produced by first-generation synchrotrons.

New Bruker Ascend™ 400 compact NMR with advanced magnets for medium and high-field NMR.



Schematic of a self-assembled energy transfer system. DNA photonic wires are used with quantum dots and various dyes to assemble a sequential fluorescence resonance energy transfer (FRET) cascade.

Nikon Eclipse C1si Confocal Microscope used for live cell imaging with advanced techniques including total internal reflection fluorescence, confocal, FRET, photoactivation, and microinjection.

Acoustics

NRL's "Reliant" unmanned undersea vehicle with towed acoustic array being deployed during a long range active acoustics experiment.

The Acoustics Division's research program spans the domains of quantum and classical physics. It addresses spatial scales from nanometers to hundreds of kilometers and temporal scales from less than microseconds to the seasonal and long-term variability of the oceans. The Division's research topics include the following:

(1) The study of the impact of riverine, ocean, and atmospheric fluid dynamics on the phase coherent properties of acoustic signals with the objective of predicting the performance variability of acoustic systems including autonomous unmanned underwater systems and their underwater acoustic communications networks;

(2) The continued development, expansion, and adaptation of full physics underwater acoustic propagation and scattering theories. The use of numerical simulations to estimate the uncertainty in acoustic field propagation simulations that is caused by limited spatial and temporal sampling of the initialization and updating sound speed fields;

(3) The measurement and theoretical description of the spatial/temporal variability of the deterministic/statistical properties of acoustic signals scattered from marine organisms, the near-surface ocean volume, the air–sea interface and the sea bottom/subbottom with the objective of reducing the impact of non-target acoustic signal clutter on naval mine countermeasures and antisubmarine warfare system performance;

(4) The prediction and measurement of the angle and frequency dependence of acoustic signals scattered and radiated by complex three-dimensional structures with application to advanced manned and unmanned mine countermeasures and antisubmarine warfare detection concepts;

(5) The design from first principles of microelectromechanical and nanotechnology-based structures (e.g., metamaterials and sensors) that have unique sound transmission, reflection, and transduction properties.

The experimental and computational components of the Division's research program require the utilization of high-performance computers, the NRL

Institute for Nanoscience experimental facilities, the University National Oceanographic Laboratory System's ships and measurement systems, and the design and use of state-of-the-art laboratory, underwater, and atmospheric research instrumentation.

At-Sea Research: The Division uses autonomous unmanned vehicles, fixed autonomous moorings, and measurement systems attached to ships. Undersea acoustic propagation and ambient noise measurements are made with a fully autonomous moored acoustic data acquisition suite composed of two 80 m, 32-channel vertical hydrophone arrays, two 600 m, 96-channel horizontal hydrophone arrays, and two 50% duty cycle programmable acoustic sources operating at center frequencies of 300 and 500 Hz. Data are acquired by two 32-channel and one 96-channel recording systems that continuously acquire 24-bit data for a minimum of 30 days.

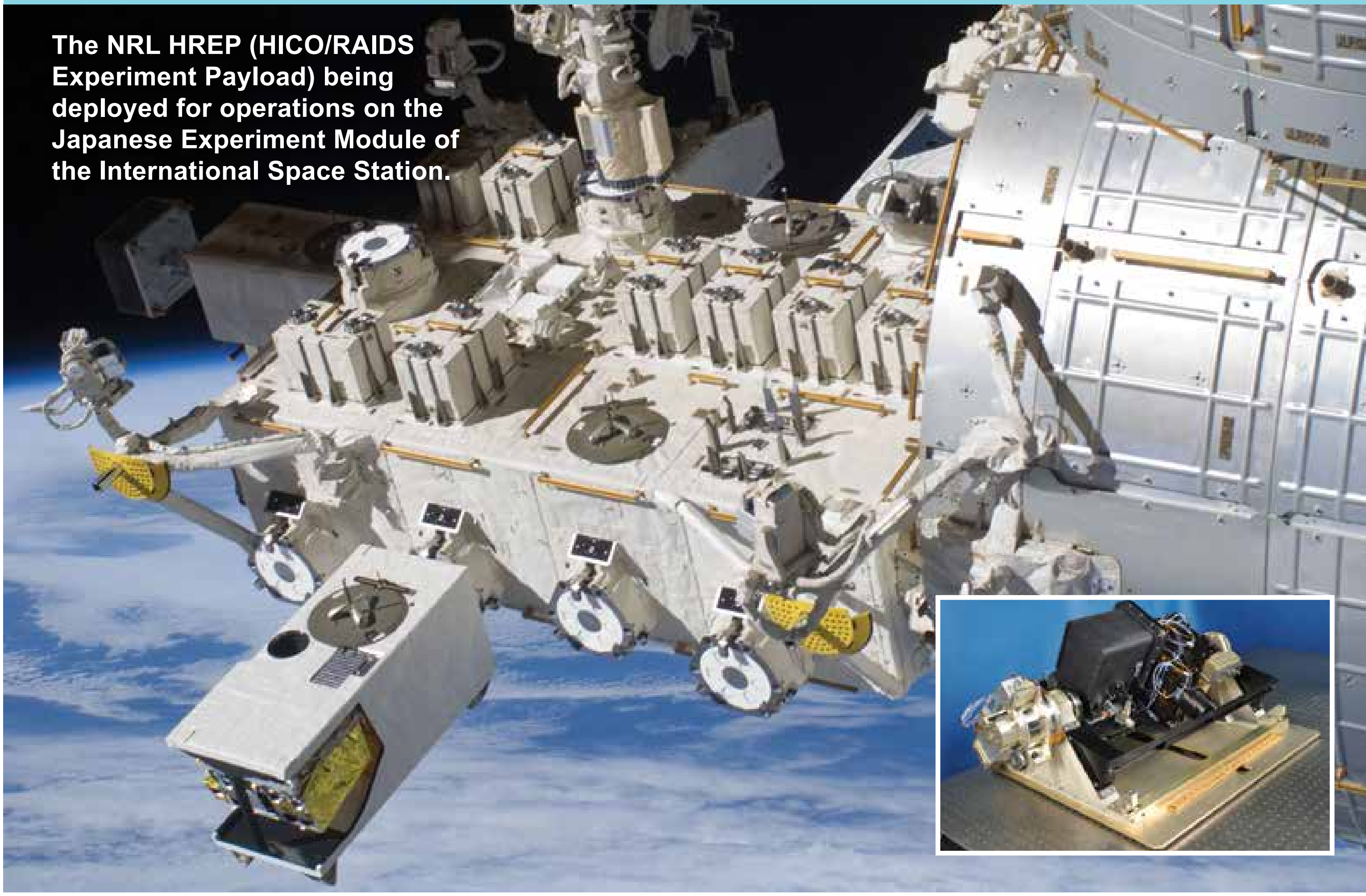
Ship-attached instruments are used to investigate the four-dimensional properties of acoustic signals scattered from the ocean's surface, bottom, and volume. They include two flex-tensional XF-4 and one ITC 2077 sound sources; a towable, vertically directional source array operating in the 1.5 to 9.5 kHz frequency band and a 64-channel broadband (500 to 3500 Hz) time reversal source-receiver array.

A 53 cm diameter Bluefin autonomous underwater vehicle (AUV) is used to test autonomous unmanned mine countermeasures, antisubmarine warfare concepts, and autonomous vehicle control algorithms designed to function in environments with unanticipated events. Underwater acoustic communications network research defines future network capacity by deploying programmable modems, two Iver-2 58 in. expandable AUVs, and two 8-channel moored/towed remotely controlled acoustic communications data acquisition modems in a variety of topologies.

Laboratory Facilities: The Acoustics Division has several nationally unique laboratory facilities. The Laboratory for Structural Acoustics supports experimental research where acoustic radiation, scattering, and surface vibration measurements of fluid-loaded and non-fluid-loaded structures are performed. A 3.7-million-liter, in-ground pool facility (17 m dia. × 15 m deep) has vibration and temperature control, anechoic interior walls, and automated three-dimensional scattering cross section measurement capabilities. Instrumentation includes compact range scattering, nearfield holography, and scanning laser Doppler vibrometry capabilities. Ultra-high-precision measurements are conducted in this pristine laboratory environment using submarine hull backing impedance simulators, torpedoes, scale-model submarine structures, and deactivated mine targets. A large acoustically treated in-air measurement facility (50 × 40 ft and 38 ft high) is used for structural acoustic and vibration measurements on satellite payload fairings, active and passive material systems for sound control, and new transducer and sensor systems. It is instrumented with robotic scanners capable of generating nearfield acoustic holography (NAH) radiation, reflection, and transmission databases. Marine sediments are replicated in tanks to study the impact of sediment burial on the structural response of mines or improvised explosive devices. In addition, a salt water tank (6 m × 6 m × 3.5 m) facility is designed to study a variety of physical phenomena under both saline and nonsaline conditions. These include air–sea interface and subsurface bubble acoustic signal absorption and scatter studies; the characterization of sound generated by laser pulses; and the effectiveness of acoustic metamaterials. A sonomagnetic measurement facility is equipped with a vibration-insulating optical table constructed from nonmagnetic materials and a single three-axis magnetometer capable of measuring fields up to ±100 μT with a 1 nT noise floor at 1 kHz. An ultrasonic measurements laboratory is used for small-scale acoustics experiments designed to measure the effectiveness of acoustic metamaterials. Two 1.2 m cubic water tanks are equipped with overhead X-Y-Z positioning systems and LabVIEW-based data acquisition systems. A fabrication workshop equipped with a Haas Mini-Mill and an Objet Connex 500 3D rapid prototyping machine support the laboratory research facilities.

Proteus LDUUV (large displacement unmanned underwater vehicle) being launched. The Acoustics Division is developing technology for this Columbia Group vehicle and recently completed measurements with it.

Remote Sensing



The NRL HREP (HICO/RAIDS Experiment Payload) being deployed for operations on the Japanese Experiment Module of the International Space Station.

The Remote Sensing Division is the Navy's center of excellence for remote sensing research and development, conducting a broad program of basic and applied research across the full electromagnetic spectrum using active and passive techniques from ground-, air-, and space-based platforms. Current applications include earth, ocean, atmospheric, astronomy, astrometry, and astrophysical science, and surveillance/reconnaissance activities including maritime domain awareness, antisubmarine warfare, and mine warfare. Special emphasis is given to developing space-based platforms and exploiting existing space systems.

A major Division research focus is environmental remote sensing of the littoral environment. Specific research areas include maritime hyperspectral imaging for in-water environmental remote sensing and land-based trafficability studies, radar measurements of the ocean surface for the remote sensing of waves and currents, and model- and laboratory-based hydrodynamics.

Airborne sensors used for characterization of the littoral environment include visible/near-infrared (VNIR) and shortwave infrared (IR) hyperspectral imagers, a VNIR multichannel and hyperspectral polarimetric imager and a nonimaging VNIR polarimetric spectrometer, longwave and midwave IR thermal cameras, an X-band, 2-channel interferometric synthetic aperture radar (SAR), and the NRL Focused Phased Array Imaging Radar (NRL FOPAIR), an X-band, high-frame-rate, polarimetric, multi-phase center SAR system.

As an outgrowth of our airborne littoral sensing program, the Division developed the Hyperspectral Imager for the Coastal Ocean (HICO), the world's first spaceborne VNIR hyperspectral sensor specifically designed for coastal maritime environmental observations. HICO was launched to the International Space Station in September 2009 and operated until September 2014, and has provided scientific imagery of varied coastal types worldwide. After a 3-year Navy mission, HICO was supported by NASA in 2013 and 2014.

New littoral research areas include the exploitation of polarized hyperspectral imaging, active (lidar-based) sensing of the water column, and multi-phase center SAR systems.

For radiometric and spectral calibration of the visible and IR imaging sensors, the Division operates a calibration facility that includes a NIST-traceable integrating sphere and a set of gas emission standards for wavelength calibration.

The Division's Free Surface Hydrodynamics Laboratory (FSHL) supports ocean remote sensing research. The lab consists of a 10 m wave tank equipped with a computer-controlled wave generator and a comprehensive set of diagnostic tools. Recent work focuses on the physics of breaking waves, their infrared signature, and their role in producing aerosols. Experiments conducted in the FSHL are also used to test and validate numerical results and analytical theories dealing with the physics of the ocean's free surface.

Non-littoral environmental research areas include the remote sensing of sea ice and soil moisture, the measurement of ocean surface winds, and middle atmospheric research. NRL (in a collaboration between the Naval Center for Space Technology and the Remote Sensing Division) developed the first space-borne polarimetric microwave radiometer, WindSat, launched in January 2003 and still operational. Its primary mission was to demonstrate the capability to remotely sense the ocean surface wind vector with a passive system. WindSat provides major risk reduction for development of the microwave imager for the next-generation Department of Defense operational environmental satellite program. WindSat data are processed at the Navy Fleet Numerical Meteorology and Oceanography Center (FNMOC), and operationally assimilated into the Navy's global weather model, as well as that of several civilian weather agencies worldwide. In addition, the Remote Sensing Division is exploiting WindSat's unique data set for the remote sensing of other environmental parameters including sea surface temperature, soil moisture, and sea ice concentration.

The Division also carries out a vigorous research program in the remote sensing of middle atmospheric constituents by ground-based millimeter-wave spectroscopy. The centerpiece of that program is the Water Vapor Millimeter-wave Spectrometer (WVMS). It is part of the international ground-based Network for Detection of Atmospheric Composition Change (NDACC), with sensors based in Lauder, New Zealand, Mauna Loa, Hawaii, and Table Mountain, California. Recently, measurements of chlorine monoxide and ozone have been added as part of a collaboration with the University of Massachusetts and the New Zealand National Institute for Water and Atmospheric Research.

The Division has research programs in astronomy and astrophysics ranging in wavelength from the optical to longwave radio (HF), with an emphasis on interferometric imaging. Facilities include the Navy Precision Optical Interferometer (NPOI), located near Flagstaff, Arizona, a joint project between the U.S. Naval Observatory and the NRL Remote Sensing Division. When completed, NPOI will be the highest-resolution ground-based optical telescope in the world. Current applications include optical astrometry, unfilled aperture imaging technologies research, astrophysical research, and (most recently) to conduct research into the imaging of deep space satellites.

As an outgrowth of this imaging research, the Division has established an adaptive/active polymer lens laboratory, consisting of a clean room environment and specialized equipment for conducting research and development, fabrication, characterization, and metrology related to adaptive polymer lenses and other types of custom polymer optics.

The Division is also at the forefront of research in low-frequency (<100 MHz) radio astronomy and associated instrumentation and interferometric imaging techniques. The Division developed and installed VHF receivers on the National Radio Astronomy Observatory's Very Large Array (VLA), has designed the next-generation HF receiver system for the EVLA (Expanded VLA), and developed imaging techniques necessary to correct for ionospheric phase disturbances, important at HF frequencies. The newly completed (November 2014) NRL VLA Low Band Ionospheric and Transient Experiment (VLITE), providing continuous imaging observations at 352 MHz with 64 MHz of bandwidth using ten VLA antennas, is a unique facility for astrophysical transient detection and ionospheric remote sensing.

The Division is also collaborating with the University of New Mexico on the Long Wavelength Array, a prototype, next-generation, HF imaging array ultimately with 200 to 300 km baselines.

Finally, the Division operates the NRL SEALAB (Scene Exploitation and Analysis Laboratory), which is the primary conduit of Division imaging research to the operational community.

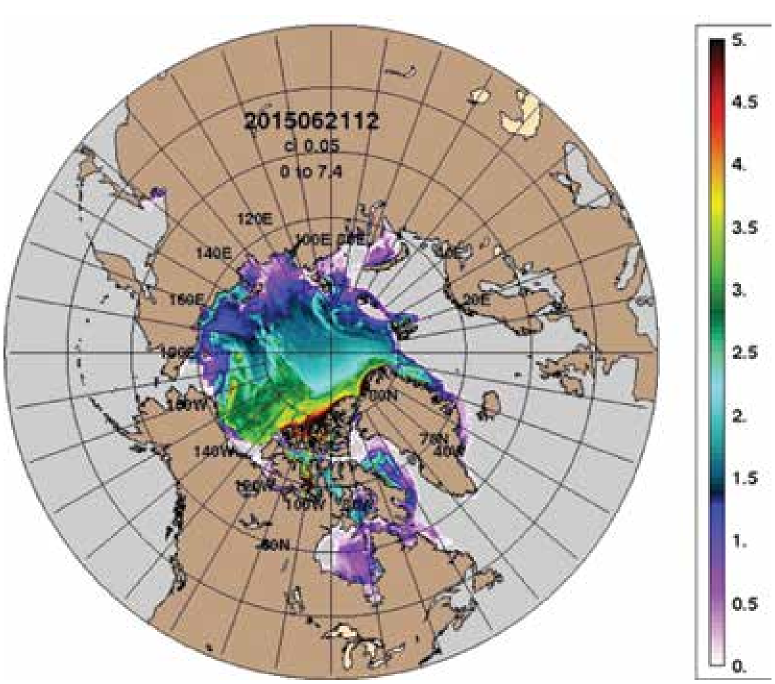
Oceanography

NRL scientists prepare to deploy a bottom-mounted SEPTR mooring in the Gulf of Mexico.

The Oceanography Division is the major center for in-house Navy research and development in oceanography. It is known nationally and internationally for its unique combination of theoretical, numerical, experimental, and remotely sensed approaches to oceanographic problems. The Division's modeling focus is on a truly integrated global to coastal strategy, from deep water including arctic regions to the coast including straits, harbors, bays, inlets, and rivers. This requires emphasis on both ocean circulation and wave/surf prediction, with additional focus on coupling the ocean models to atmospheric, ice, biological, optical, and sediment models. This includes processing and analysis of satellite and in-water observations, development of numerical model systems, and using advanced data assimilation techniques for predicting the ocean environment. This modeling is conducted on the Navy's and Department of Defense's most powerful vector and parallel processing machines. The Division's in-house Ocean Dynamics and Prediction Computational Network Facility provides computer services to scientists for program development, graphics, data processing, and storage, and provides network connectivity to other Navy and DoD sites including the High Performance Computing centers. The computational system enables leading-edge oceanographic numerical prediction research applicable to Navy operations affected by environmental variations at scales of meters to hundreds of kilometers and time scales of seconds to weeks. To study the results of this intense modeling effort, the Division operates a number of highly sophisticated graphic systems to visualize ocean and coastal dynamic processes. Problems addressed cover a wide scope of physics including parameterization of oceanic processes, construction and analysis of ocean models and forecast systems, basic and applied research of ocean dynamics, surface waves, thermohaline circulation, nearshore circulation, estuarine and riverine modeling, arctic ice modeling, internal waves, and ocean/atmosphere/wave/ice coupling. Additional emphasis is on optimization of underwater, airborne, and satellite observing systems, representation of ocean processes affecting temperature, salinity, and mixed-layer depth, uncertainty analysis in coupled systems, ensemble and probabilistic ocean forecasting, targeting ocean observations, representing probability in ocean/acoustic systems, and satellite-observed surface heat fluxes. The end goal is to build cutting-edge technology systems that transition to operational forecast centers.

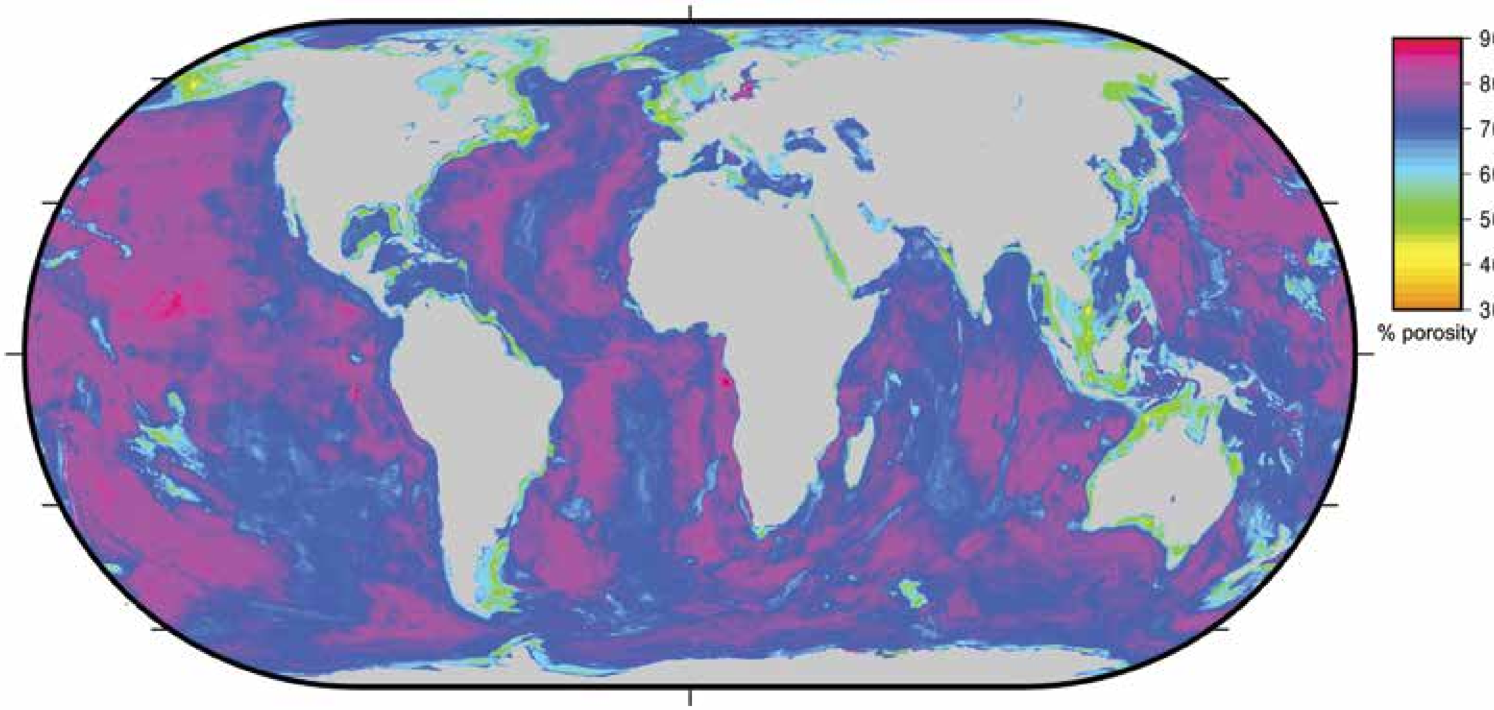
The Division's Ocean Sciences Branch conducts basic and applied research in ocean physics, air–sea interaction, ocean optics, coupled physical bio-optical modeling, and marine microbially influenced corrosion. Emphasis of this research is on understanding the oceans' physical processes and their interactions with the atmosphere and biological/chemical systems at scales ranging from basin-scale to microscale. Numerical and analytical models are developed and tested in laboratory and field experiments. The results of this research support the Navy's operational capability for predictions of oceanic atmospheric exchanges, acoustic propagation/detection, light transmission/emission, and influences of microbes on marine corrosion. The seagoing experimental programs of the Division range worldwide. Unique measurement systems include a wave measurement system to acquire in situ spatial properties of water waves; a salinity mapper that acquires images of spatial and temporal sea surface salinity variabilities in littoral regions; an integrated absorption cavity and optical profiler system; a towed optical hyperspectral array and a Shipboard Lidar Optical Profiler (SLOP) for studying ocean optical characteristics; self-contained, bottom-mounted, upward-looking acoustic Doppler current profilers (ADCPs) for measuring ocean variability; and a Shallow water Environmental Profiler in Trawl-safe, Real-time configuration (SEPTR). A newly acquired Rayleigh–Bénard convective tank and a hybrid underwater camera support the Division's ocean optics programs providing object detection and identification in extremely turbid underwater environments. Instruments for sensing the littoral environment include a Vertical Microstructure Profiler (VMP), a Scanfish, and four Slocum Gliders equipped with a microstructure (turbulence) package.

The Division's remote sensing research focuses on radiative transfer theory, optical ocean instrumentation, lasers and underwater imaging and vision, satellite and aircraft remote sensing, and remote sensing of bio-optical signatures. The research includes applying aircraft and satellite ocean color and thermal infrared signatures for understanding the biogeochemical cycles in the surface ocean. Additional emphasis is on algorithm and model development using satellite and aircraft data (SeaWifs, MODIS, MERIS, AVHRR, VIIRS, OCM, GOCI, HICO, and CASI) to address the spatial and temporal variability of coastal optical properties.



Arctic ice thickness (meters) from the Coupled HYCOM/CICE System for June 21, 2015.

Marine Geosciences



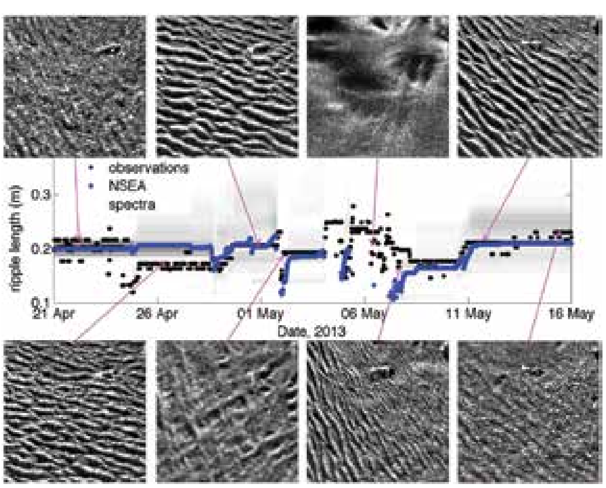
Geophysicists map global seafloor porosity with highest fidelity ever using machine learning techniques.

The Marine Geosciences Division is the major Navy in-house center for research and development in marine geology, geophysics, sediment dynamics, geodesy, geoacoustics, geotechnology, and geospatial information and systems, with its research focused in three thrust areas:

Characterization and Prediction in Seafloor and Terrestrial Regions. Research subthrusts: (1) Collaborative research continues with Remote Sensing Division scientists to exploit remotely sensed hyperspectral information of subsurface sediment character and structure to estimate trafficability parameters, including complex and heterogeneous soils. Moisture content and density can be used, along with other remotely measured quantities, as inputs to geotechnical models to provide estimates of soil strength and bearing capacity properties. Trafficability parameters can then be evaluated from these properties. (2) Division researchers participated in the Navy's ICe EXercise (ICEX) 2016, sponsored by Arctic Submarine Lab (ASL) 150 nautical miles off the North Slope of Alaska, as part of their Sea Ice Physics 6.1 project to use ultra-wideband, low-frequency, polarimetric synthetic aperture radar (SAR) to remotely sense bulk properties of sea-ice over broad two-dimensional areas. This project is a follow-on to collaborative research with Remote Sensing and Oceanography Division scientists to utilize a prototype airborne SAR, light detection and ranging (lidar), and snow radar instrument suite to calibrate CryoSat2 satellite-derived snow and ice measurements and the Navy's ice–ocean coupled numerical model. (3) As part of the Carbon Flux project, machine-learning techniques have been applied to predict seafloor properties where they cannot be directly measured. The ocean is far too vast for complete, direct sampling of parameters such as seafloor porosity, which are critically important for a variety of fields including seafloor acoustics, chemical oceanography, climate modeling, microbiology, hazard assessment, and economic resource development. Machine learning techniques find correlations between the desired quantity, in this case seafloor porosity, and other, well-known quantities (e.g., distance from the coast, bathymetry, etc.), as well as derivatives and statistics of the well-known quantities. The correlations are then used to predict porosity at any point on the seafloor. A new global modeling program will focus on extending these techniques in concert with deterministic sediment physics modeling to predict acoustic properties everywhere on the seafloor.

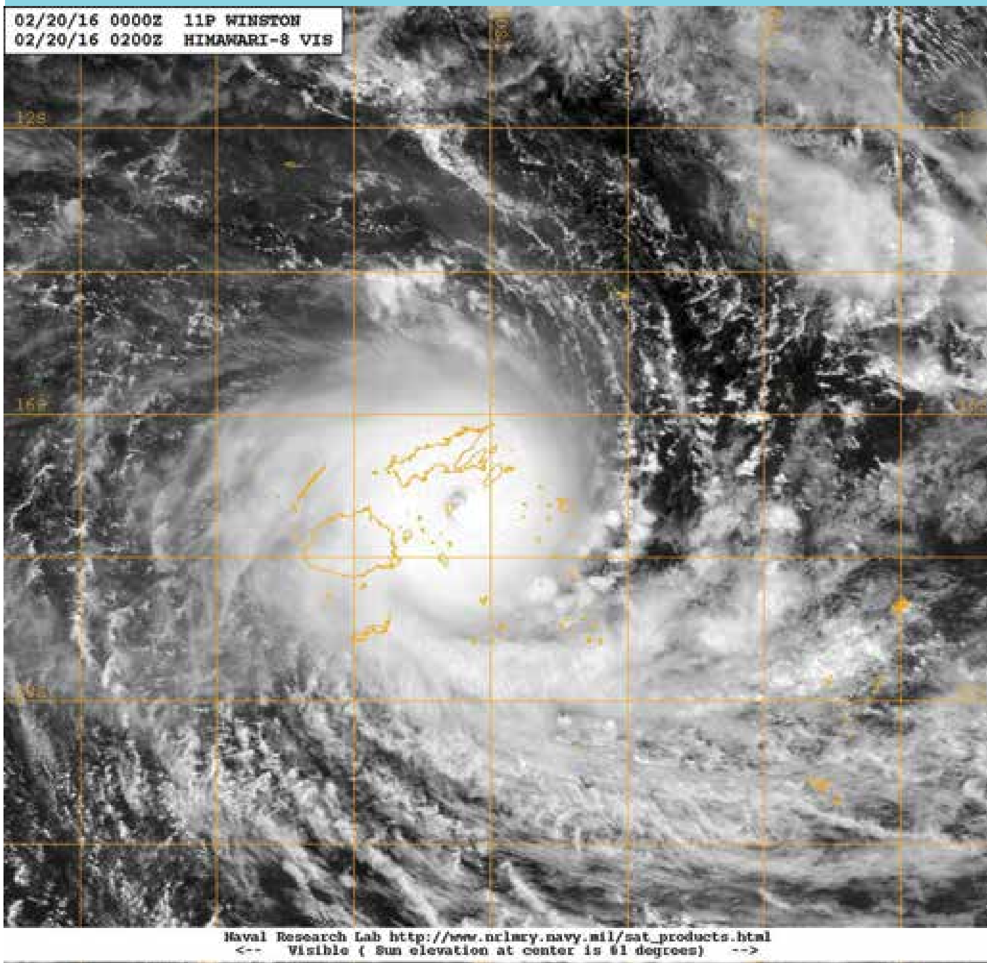
Dynamic Littoral and Riverine Processes. Research subthrusts: (1) Development of the new Naval Seafloor Evolution Archetype (NSEA) was recently completed. The spectral ripple model, NSEA, predicts variations in seafloor roughness given measured or forecasted wave conditions in sandy environments. The time-dependency is a function of equilibrium ripple geometries and the amount of sediment transport needed to reach an equilibrium state, which is dependent on the existence of relict ripples. Spectral decay due to bioturbation is incorporated as a diffusive process. The model predicts the evolution of spectral ripple wavelengths that are in good agreement with observations. (2) Division scientists developed a new inversion method for estimating depth and discharge in open channel flow hydraulics using observations of surface currents and water surface elevation. The inversion method was validated on a 14 m × 10 m grid using remotely sensed surface velocity measurements and water surface elevation on the Kootenai River in Idaho. (3) Marine biogeochemists study the impact of hypoxic zones in the Gulf of Mexico on benthic communities and on surficial sediment. (4) The Division continues its modeling of sediment transport phenomena across many orders of magnitude, from the discrete particle scale (where the motions of individual sand grains are simulated) to the continuum scale (where sand ripples and bathymetric changes are predicted). (5) Development continues on a predictive model for the mechanical strength and erodibility of soft, cohesive sediments by analyzing the physicochemical, micromechanical, and bulk mechanical responses of cohesive sediment constituents under controlled manipulation of variables including hydrodynamics, salinity, and organic matter speciation.

Geospatial Sciences and Technology. Research subthrusts: (1) The Division continued its research into modernization of production processes for navigation and planning charts with the National Geospatial-Intelligence Agency's (NGA) Maritime and Aeronautical production offices. New versions of the Digital Nautical Chart verification software and Seamless Enroute Chart production system were delivered. This includes the first dynamic, full-color compressed raster chart production system. (2) The Division is also a key performer for NGA's Innovative GEOINT App Provider Program (IGAPP). NRL provides all high performance data services for this effort using the NRL-created Tile Server system. NRL's Tile Server system utilizes technology from over 10 NRL patents. (3) Division scientists delivered Environmental Post Mission Analysis software for use in the Littoral Combat Ship Mine Countermeasures Mission Module, utilizing on-scene data collections to update environmental databases and reduce timelines for detecting mine-like changes on the seabed. (4) The Division grew its human factors research to improve Navy warfighter performance using geospatial applications and to further automate Navy processes. This included extensive user trials for the creation of the prototype watchfloor for Command Task Group 80.7 Physical Battlespace Awareness Maritime Operations Center. (5) The Division continued development of the Geospatial Area Folders concept which provides the ability to rapidly create geospatially enabled intelligence products from multisource intelligence data, reducing regional headquarters production timelines by 80% to deliver actionable intelligence to the warfighter. Seven Mine Warfare Area Folder (MWAF) systems were transitioned into operational use, with system delivery and training provided to CTF 52 in Bahrain, MCMRON 7 in Japan, and operational headquarters in the United States. (6) Division scientists started a new hybrid architecture research program to investigate new hardware configurations to improve performance of Navy processing algorithms. Early results indicate process speedups of over 1000 times using innovative new memory architectures and updated algorithms.



NSEA spectral ripple model compared to observations. Middle panel: Observed peak ripple wavelength (black circles) plotted over 26 days with the modeled peak ripple wavelength (blue circles) and the modeled seafloor spectra (grayscale contour). Top and bottom panels: Sonar images of the seafloor with arrows pointing to the corresponding times.

Marine Meteorology

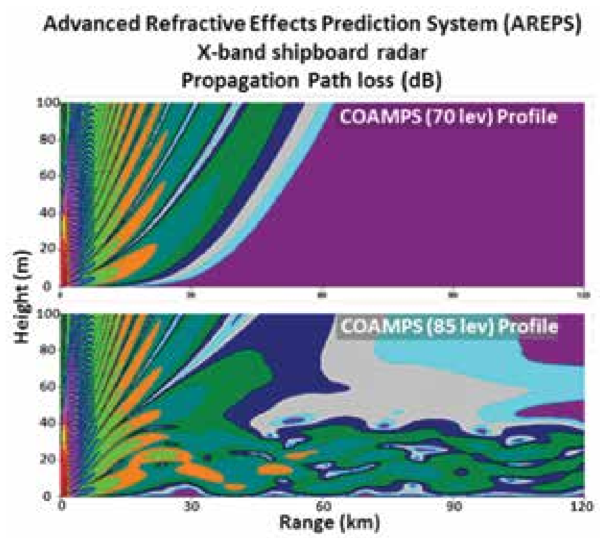


Cyclone Winston over the Fiji Islands as seen in visible imagery produced at NRL Monterey from Himawari-8 Advanced Himawari Imager (AHI) data.

The Marine Meteorology Division, located in Monterey, California, conducts cutting-edge basic and applied research in the atmospheric sciences. The Division develops high resolution meteorological analysis and prediction systems and other decision support products to support Navy, Department of Defense (DoD), and other customers operating at theater, operational, and tactical levels. The Division is collocated with the Fleet Numerical Meteorology and Oceanography Center (FNMOC), the Navy's operational production center for numerical weather prediction (NWP) and satellite imagery interpretation.

The Division's Atmospheric Dynamics and Prediction Branch studies atmospheric processes such as air–sea–ice interaction, tropical cyclone intensification, atmospheric dynamics, and cloud/aerosol physics. The Branch develops numerical weather analysis and prediction systems and coupled air/land/ocean/ice systems for operational use using local high-performance computing resources and offsite DoD Supercomputing Resource Centers, as well as FNMOC assets. Leveraging these theoretical studies and field data collected from around the world, the Division's Meteorological Applications Development Branch develops, improves, and transitions satellite imagery products, decision aids, and probabilistic prediction tools that provide unique and tailored guidance used by Fleet and Marine forces around the globe.

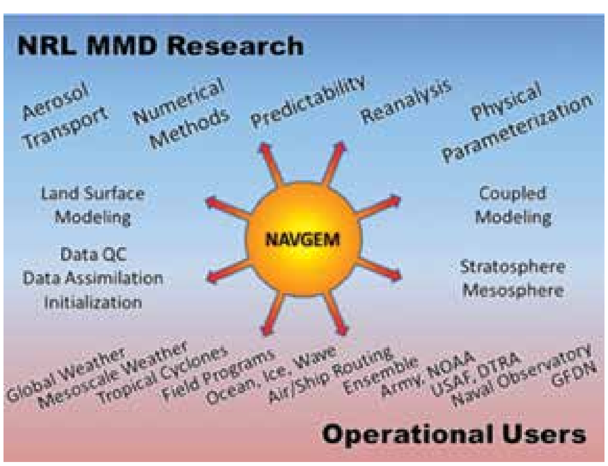
The heart of the Division's research program into atmospheric processes is the Navy Global Environmental Model (NAVGEM) which ties together R&D in regional and tactical scale NWP models, systems to assimilate millions of weather observations per day in which to produce highly accurate long-range predictions to support Navy planning and operations. The NRL Advanced Variational Data Assimilation System – Advanced Representer (NAVDAS-AR) merges millions of observations separated by time and distance from which NAVGEM produces a coherent picture of the atmosphere and long-range predictions. The coupled



Comparison of AREPS predictions using high-resolution COAMPS in the lower atmosphere.

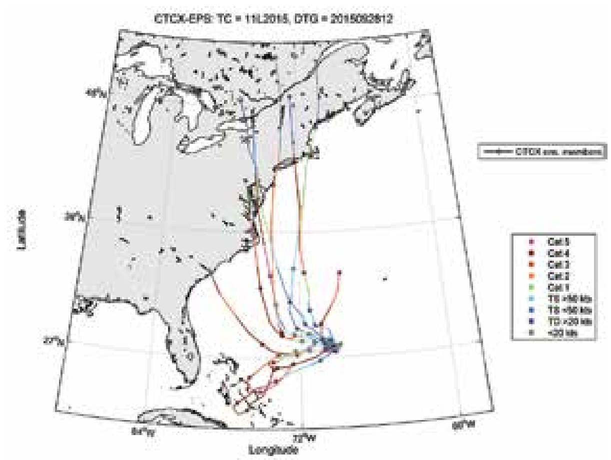
Ocean-Atmosphere Mesoscale Prediction System (COAMPS) then uses NAVGEM's initial output to provide higher resolution tactical scale forecasts.

The Division's regional-scale NWP prowess is provided operationally via the COAMPS-On Scene system (COAMPS-OS) which allows users to easily set up complex NWP models via "reach-back," create tailored operational forecasts, and post-process model output into tactically relevant advanced decision support applications. Other applications further exploit meteorological information for decision superiority using cornerstone operational applications including the Joint METOC Viewer (JMV), Automated Tropical Cyclone Forecasting (ATCF) system, automated ship routing, Atmospheric Acoustic Propagation (AAP) for helicopters, and the Advanced Refractive Effects Prediction System (AREPS) for electromagnetic propagation predictions.



Relationship between NAVGEM and other NRL Marine Meteorology Division R&D programs.

The Division advances the state of the art of satellite-derived environmental characterization and tropical cyclone structure and intensity analysis. Next-generation satellite data provides enhanced spectral coverage, increased spatial resolution, and quicker temporal refresh of these products. Exploitation of these high volume data sets is accomplished through the NRL MMD-developed Geo-located Information Processing System (GeoIPS). GeoIPS is a portable data ingest and processing system for R&D, near real time demonstrations, and efficient transitions to operations.



Real-time ensemble forecasts of Hurricane Joaquin for 1200 GMT, September 28, 2015 from COAMPS showing large uncertainty in predicted track and intensity.

The Division performs end-to-end studies of electro-optical (EO) performance predictions ranging from studies of basic aerosol, cloud, and radiation processes; to projects that integrate theory, field research, remote sensing and numerical aerosol and EO prediction at global to mesoscales. The Division is unique in the community in its depth of capabilities to develop and support systems that can globally characterize the EO environment, as well as support of Navy and DoD tactical decision support products.

Space Science

Michelson Interferometer for Global High-resolution Thermospheric Imaging (MIGHTI) spaceflight instrument in an NRL Space Science Division cleanroom. On orbit, MIGHTI will measure neutral winds and temperature in the thermosphere to assess the dramatic variability of the Earth's ionosphere.

The Space Science Division conducts a broad-spectrum RDT&E program in solar-terrestrial physics, astrophysics, upper/middle atmospheric science, and astronomy. Division researchers conceive, plan, and execute scientific research and development programs and transition the results to operational use. They develop instruments to be flown on satellites, sounding rockets, and balloons; and ground-based facilities and mathematical models. The Division's primary objective is to perform foundational discovery research to ensure Navy and Marine Corps access to critical space capabilities and space force enhancement capabilities on the ground, at sea, and in a contested space environment.

The Division's Vacuum Ultraviolet Solar Instrument Test (SIT) facility is an ultra-clean solar instrument test facility designed to satisfy the rigorous contamination requirements of state-of-the-art solar spaceflight instruments. The facility has a 400 ft^2 Class 10 clean room and a large Solar Coronagraph Optical Test Chamber (SCOTCH). The SIT clean room is ideally suited for assembly and test of contamination-sensitive spaceflight instrumentation. It contains a large vibration-isolated optical bench and a 1-ton capacity overhead crane. The SCOTCH consists of a large vacuum tank and a precision instrument-pointing table. The Division also maintains extensive facilities for supporting ultraviolet (UV) spectroscopy sounding rocket programs. These facilities include a dedicated Class 1000 instrument clean room, and a gray room area for assembling and testing the rocket payloads that incorporates all of the fixtures required for safe handling of payloads. Further, the Division rocket facilities include a large UV optical test chamber that is additionally equipped with a large vibration- and thermal-isolated optical bench for telescope testing, which allows the laboratory area to be turned into a schlieren facility.

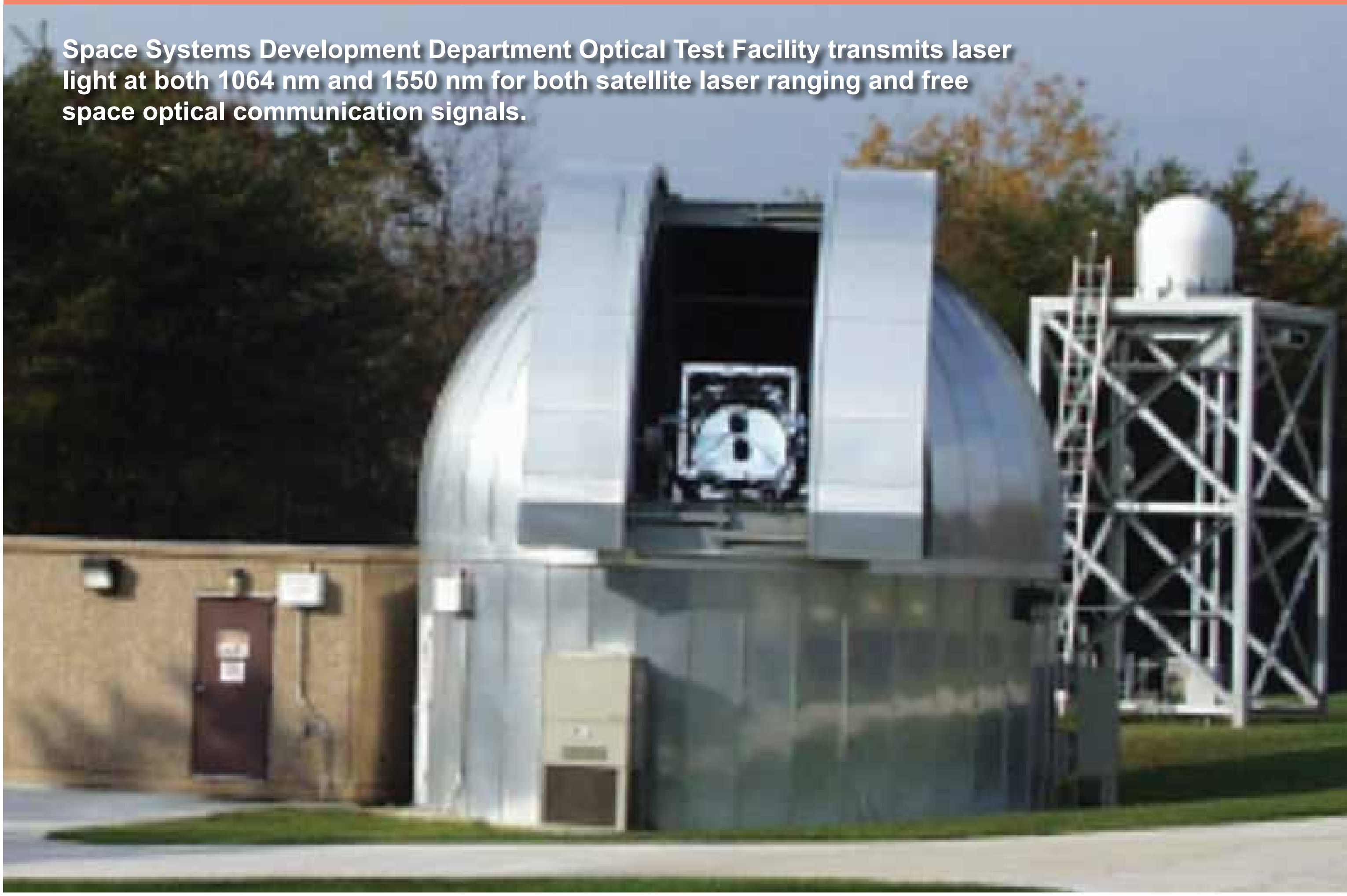
The Division has a wide range of new satellite, rocket, balloon, and ground-based instruments under development. These include the SoloHI heliospheric imager that will image both the quasi-steady flow and transient disturbances in the solar wind when aloft on board the Solar Orbiter mission; the Compact COROnagraph (CCOR), an elegant, externally occulted instrument that uses a single-stage optical design with two lens groups, a polarization analyzer, and a spectral filter to achieve performance comparable to the traditional three-stage Lyot coronagraph but with significantly lower mass and volume than the traditional design; and the NRL-led SuperMISTI detection system, intended to demonstrate standoff detection, identification and imaging of radiological/nuclear weapons of mass destruction (WMD) in maritime environments.

Advanced space-based research is performed in a number of areas. Division experiments are measuring the Earth's thermosphere and ionosphere to improve space weather forecasting for these near-space atmospheric regions that significantly influence the performance of important operational systems such as GPS navigation, communication, and space debris tracking. In August 2013, the Fermi Gamma-ray Space Telescope, major portions of which were developed and tested by NRL's Space Science Division and Spacecraft Engineering Department, completed five years of successful operation on orbit. Division scientists have had lead roles in several key scientific discoveries using Fermi, including: confirmation of the long-standing belief that shocks formed from exploding stars are the source of the high-energy cosmic rays seen at Earth; creation of a highly efficient means of discovering new pulsars, the rapidly rotating cores of dead stars that serve as precise astrophysical clocks; and discovery that our Sun accelerates particles to extreme energies even in relatively weak flares, and does so for hours after the impulsive event. Two Space Science Division-led heliophysics space instrument capabilities, the Large Angle Spectrometric and Coronagraphic Telescope (LASCO) on the SOHO mission and the Sun-Earth Connection Coronal Heliospheric Investigation (SECCHI) on the STEREO mission, are continuing to advance understanding of the solar corona and the importance of coronal mass ejections in determining space weather at Earth.

Division scientists, using the Division network of computers and workstations and other connected high performance computing assets, develop and maintain physical models in support of their research. These include research to extend the operational Navy Global Environmental Model (NAVGEM) from its current upper boundary to altitudes of ~100 km; and SoftWare for Optimization of Radiation Detectors (SWORD), a vertically integrated radiation transport software tool for graphically setting up, running, and analyzing results from numerical simulation of high energy radiation detection systems and other systems that operation in a high energy radiation environment.

NRL's major role in the Fermi mission (launch 2008, upper left) has enabled broadly based astrophysical investigations including the gamma-ray sky map (upper right) identifying over 3000 point sources and new insight into particle acceleration and radiations from pulsars, supernova remnants, active galactic nuclei, and many other topics. Space science research in detector design enabled by NRL's Institute for Nanoscience (NSI) has resulted in three pending patents relating to "slim edge" detectors (middle left) and charge control using atomic layer deposition, and three patents on deep reactive ion etching of detectors (lower left). Other division work at the NSI has resulted in patents for a fabrication method for nanometer-scale level structures and for detecting chemical or radiological agents using electrophoretic displays. The J-PEX extreme-ultraviolet sounding rocket experiment (lower center) provided unprecedented spectral resolution on white dwarf stars. Division research in radiological/nuclear weapons of mass destruction (WMD) detection resulted in the dual container SuperMISTI detection system (middle right, in transport to Norfolk maritime testing) providing standoff detection and imaging of WMD. Image (lower right) shows SuperMISTI image of radiation source (blue block) hidden in the hold of USS *Cape Chalmers*.

Space Systems Development Department



Space Systems Development Department Optical Test Facility transmits laser light at both 1064 nm and 1550 nm for both satellite laser ranging and free space optical communication signals.

The Space Systems Development Department (SSDD) is responsible for the end-to-end definition, design, development, integration, test, and operation of space systems that satisfy naval and national defense requirements.

The total system engineering philosophy employed by the SSDD enables seamless sensor-to-shooter capabilities to be deployed that optimize the interfaces between command and control, on-orbit satellite collection, and onboard and ground processing functions; the dissemination of data to tactical and national users; and the design of tools that provide for the automated correlation and fusion of collected information with other sources.

Research and development is conducted in the areas of space system architectures; advanced mission data processing and data analysis techniques; advanced information systems concepts, including enterprise and cloud computing and networking of space, air, ground, and subsurface sensors; and mission simulation techniques. Intelligence collection, advanced RF, optical, and laser communication, satellite laser ranging, digital signal processing, data management, and space navigation systems are constantly improved upon to satisfy evolving requirements. These systems are engineered for maximum reuse and interoperability.

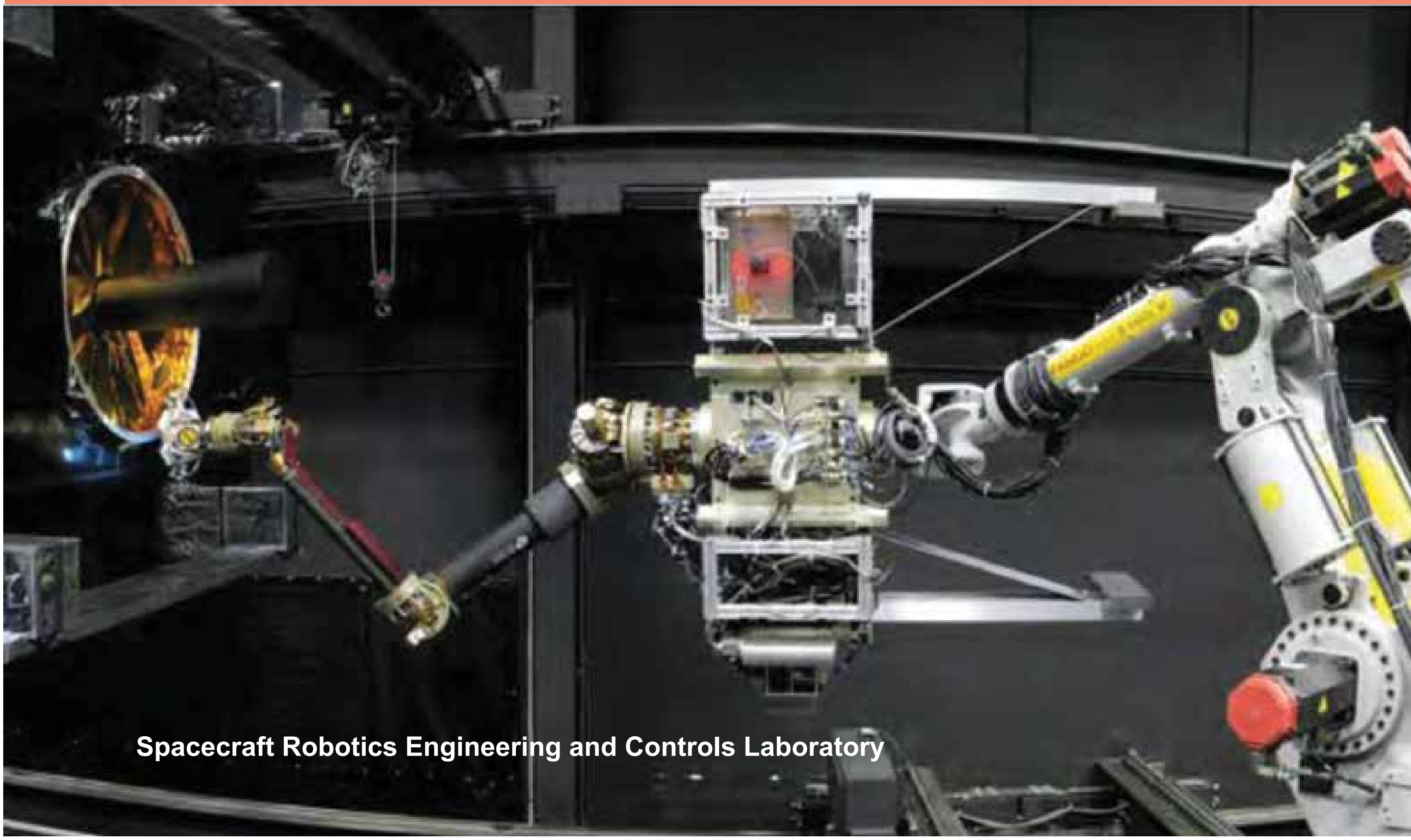
Having conceived of and developed the payload for the first Global Positioning System (GPS) satellite, the SSDD continues to be a center of excellence in the research and development of advanced GPS technology. Advanced theoretical and experimental investigations are applied to expanding the design and interoperability of systems used for a wide range of military, space, geodetic, and time dissemination applications. These investigations involve critical precise time generation and measurement technology for passive and active ranging techniques incorporating advanced data transmission and signal design. Precise time and time interval research conducted involves theoretical and experimental development of atomic time/frequency standards, instrumentation, and timekeeping to support highly precise and accurate timescale systems in scientific and military use. Net-centric systems are critically dependent on highly accurate and stable time/frequency standards coordinated to a common time-scale through the diverse dissemination comparison techniques developed within the SSDD.

The Precision Clock Evaluation Facility (PCEF) is one of the major facilities within NRL's Naval Center for Space Technology. The PCEF was developed to support development of high-precision clocks for GPS spacecraft and ground applications, primarily atomic standards. Space atomic clocks are evaluated, qualified, and acceptance tested for space flight using the assets of this facility. Testing performed includes long-term and short-term performance evaluation, and environmental testing (including shock and vibration). Investigations of on-orbit anomalies are performed within the PCEF to attempt to duplicate similar effects in space-qualified hardware under controlled conditions. The facility was originally developed to evaluate developments in the Global Positioning System concept development program (Block I) and expanded for the dedicated space clock development conducted during operational system development and deployment. The ability to evaluate and test highly precise atomic clocks, especially in a space environment, requires unique facilities, precise time and frequency references, and precise instrumentation. The primary time and frequency reference for the PCEF is a specially designed environmental chamber housing a number of hydrogen masers combined with measurement equipment permitting a realization of Coordinated Universal Time (UTC) to be maintained as UTC (NRL) in cooperation with the International Bureau of Weights and Measures (BIPM) for reference and research purposes.

The Naval Center for Space Technology's Precision Clock Evaluation Facility (PCEF).

In addition to a wide array of test tools and facilities, the Department operates several field sites including the Midway Research Center facility in Stafford, Virginia; the Blossom Point Tracking Facility in Welcome, Maryland; and the Chesapeake Bay Detachment Radar Range in Chesapeake Beach, Maryland.

Spacecraft Engineering Department



Spacecraft Robotics Engineering and Controls Laboratory

The Spacecraft Engineering Department (SED) and the Space Systems Development Department, together comprising NRL's Naval Center for Space Technology (NCST), cooperatively develop space systems to respond to Navy, Department of Defense, and national mission requirements with improved performance, capacity, reliability, efficiency, and life cycle cost.

The SED facilities that support this work include integration and test highbays, large and small anechoic radio frequency chambers, varying levels of clean rooms, shock and vibration tables, an acoustic reverberation chamber, battery laboratory, large and small thermal/vacuum test chambers, a thermal systems integration and test laboratory, two-phase heat transfer facility, a spin test facility, a static loads test facility, and a spacecraft robotics engineering and control system interaction laboratory.

Integration and Test Facilities: The department maintains a wide range of specialized RF chambers for test of antennas, receivers, transmitters, electronics, and other flight systems. Two main anechoic chambers are used for the test and verification of antennas and flight systems. The tapered chamber is 31 × 31 × 120 ft, with a 100 ft measurement distance; it is instrumented from 100 MHz to 18 GHz for radiation patterns, and is regularly used for electromagnetic interference (EMI) measurements as well. The rectangular chamber is 10 × 12 × 20 ft, with a 15 ft measurement distance, and is instrumented from 1 to 330 GHz. There is also a 3 × 3 ft millimeter-wave near-field scanner that is also instrumented up to 330 GHz, but capable of measurements up to 550 GHz. All the measurement facilities are computer-controlled and fully automated, allowing multiple antennas and polarizations to be measured at the same time. A third RF chamber is dedicated to electromagnetic interference/radio frequency interference (EMI/RFI) testing. This welded steel chamber measures 23 × 23 × 20 ft and provides as much as 120 dB shielding effectiveness up to 18 GHz and 100 dB from 18 to 50 GHz. The chamber uses a hybrid anechoic material consisting of wideband pyramidal absorbers and ferrite tiles for performance from 20 MHz to 50 GHz. The EMI chamber is equipped with instrumentation to perform the full range of MIL-STD-461 EMI qualification testing. A 10 ft high × 11 ft wide sliding bladder door allows easy access of large test items to the main chamber.

The Laminar Flow Clean Room provides an ISO 5 (Class 100) ultraclean environment for the cleaning, assembly, and acceptance testing of contamination-sensitive spacecraft components, and integration of complete spacecraft subsystems. The facility is used primarily to support spacecraft propulsion systems but has been used to support all spacecraft electrical, electronic, and mechanical subsystems.

The Vibration Test Facility, which simulates the various vibration-loading environments present during flight operations and demonstrates compliance to design specifications, consists of the following shakers: Unholtz-Dickie T5000 50K lbf random 2-in. DA stroke, Ling 4022 30K lbf random 2-in. DA stroke, Ling 2022 16K lbf random 2-in. DA stroke, and a Ling 335 16K lbf random 1-in. DA stroke.

The Acoustic Reverberation Simulation Facility is a 10,000 ft^3 reverberation chamber that simulates the acoustic environment that spacecraft will experience during launch. The maximum capable sound pressure level is approximately 152 dB.

The Battery Laboratory supports design, development, and testing for space and terrestrial battery hardware. The lab consists of a MACCOR battery test system, which is a fully automated computerized test system that can cycle multiple batteries/cells simultaneously; and a Thermotron thermal chamber to support testing at temperature extremes.

The Thermal Fabrication and Test Facility supports the design, fabrication, installation, and verification of spacecraft thermal control systems. It also provides for the analytical thermal design and analysis of any spacecraft.

The Advanced Two Phase Heat Transfer Facility provides for concept development, performance verification, and basic research with respect to all manner of high performance heat pipes, capillary and mechanically pumped fluid loops and advanced modeling methods comprised of both commercially available and internally developed analytical codes to include computational fluid dynamics techniques.

The Thermal Vacuum Test Facility consists of one large, two medium, and several small chambers. The large chamber is a 16 ft diameter by 30 ft long horizontal end loading cylinder; the medium chambers are 7 ft diameter by 8 ft tall vertical bottom loading cylinders. The large and one medium chamber are cryogenic pumped, providing an oil-free vacuum environment. The other medium chamber has a diffusion pump system capable of evacuation rates similar to the rates that occur during launch ascent. All three chambers are equipped with gaseous nitrogen conditioned thermal shrouds capable of temperatures between –150 °C and +125 °C. The large chamber and both medium chambers are enclosed within a 2100 ft^2 clean room that is specified at ISO 7 (Class 10,000) and certified to ISO 5 (Class 100).

The Spin Test Facility contains a Space Electronics model Product of Inertia-3500 Spin Balance Instrument which is a self-contained and fully automatic system for the measurement of dynamic balance, product of inertia, moment of inertia, and center of gravity offset (dynamic) in a single setup.

The Static Loads Test Facility provides the capability to perform modal survey testing on a wide variety of spacecraft and structures. It consists of two 6 ft × 12 ft × 6 in. thick, ~15,500 lb steel plates (attachable) with floating base, six 75 Flb stinger shakers (1/2-in. DA stroke), two 250 Flb stinger shakers (4-in. DA stroke), and a ~300-channel data acquisition system (expandable).

Spacecraft Robotics Engineering and Controls Laboratory: This facility contains the Proximity Operations Testbed (POT), which is the largest dual-platform motion simulator of its kind, and the Gravity Offset Table (GOT). The POT allows engineers to simulate the rendezvous and proximity operations of spacecraft docking and robotic grappling of target satellites. The test bed encompasses the entire 45 ft × 100 ft Space Robotics Laboratory, providing a large area to perform spacecraft maneuvers on two motion simulation platforms. The Gravity Offset Table is a 77,000 lb solid slab of granite measuring 20 ft × 15 ft × 1.5 ft thick. It is ground to a precision flatness within 0.0018 inches across its surface. The GOT is used to simulate satellite rendezvous and contact dynamics under conditions where the hardware is able to float freely on a cushion of air across the flat surface, nearly negating the effects of gravity and friction on the overall body mass. This is thought to be the largest single slab precision granite table in the country. Due to its large size, it allows engineers to simulate servicing of very large objects with significant structural flexibility to a degree of accuracy unmatched by any other space robotics facility. The robotics laboratory supports research in the emerging field of space robotics including autonomous rendezvous and capture, remote assembly operations, and machine learning. It allows full-scale, hardware-in-the-loop testing of flight mechanisms, sensors, and logic of space robotic systems.

Technology Transfer Office

The NRL Technology Transfer Office (TTO) is responsible for NRL's implementation of the Federal Technology Transfer Act. It facilitates the transfer of NRL's innovative technologies for public benefit by marketing NRL technologies and by negotiating patent license agreements and Cooperative Research and Development Agreements (CRADAs).

NRL's patented polysiloxane direct-to-metal nonskid coating has improved durability, color retention, and reduced VOC.

TTO markets NRL technology through its Web site, by exhibiting at trade shows and scientific conferences, posting videos on NRL's social media sites, and through DoD-contracted Partnership Intermediaries such as TechLink. It also works with state and local economic development offices to identify small companies manufacturing and selling related technologies.

A license grants a company the right to make, use, and sell NRL technologies commercially in exchange for equitable licensing fees and royalties. Revenue is distributed among inventors and NRL's general fund. TTO reviews the commercialization plan submitted by the potential licensee in support of its application for a license. The plan must provide information on the licensee's capabilities, proposed development expenditures, a time line to commercialization, and an assessment of the planned market.

A license may be exclusive, partially exclusive (exclusive for a particular field of use or geographic area), or non-exclusive. Once a license is executed, TTO monitors the licensee for timely payments and for its diligence in commercializing the licensed invention.

TTO also negotiates Government Purpose Licenses to transition NRL technologies for manufacture and sale solely for Navy and other U.S. Government purposes.

CRADAs provide a vehicle for NRL scientists and engineers to collaborate with their counterparts in industry, academia, and state and local governments. Under a CRADA, a company may provide funding for collaborative work between it and NRL and is granted an exclusive option to license technologies developed under that CRADA's Statement of Work (SOW). TTO works with the NRL scientist to develop a SOW that has sufficient detail to define the scope of the CRADA partner's rights.

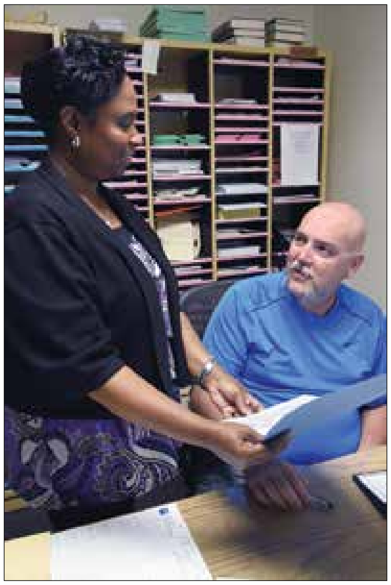
Technical Information Services

The Technical Information Services (TIS) Branch combines publication, printing and duplication, graphics, photographic and photo-archiving services, video production, and exhibit support into an integrated organization. Publication services include writing, editing, composition, publications consultation and production, and printing management. The Service Desk provides quick turnaround digital black and white and color copying/printing, CD/DVD duplication, as well as passport and ISOPREP photos. Graphic support includes technical and scientific illustrations, computer graphics, design services, display and conference posters, and framing. Large format printers offer exceptional color print quality up to 1200 dpi and produce indoor posters and signs up to 56 inches. Lamination and mounting are available. Photographic services include digital still camera coverage for data documentation, both at NRL and in the field. Photographic images are captured with state-of-the-art digital cameras and can be output to a variety of archival media. Photofinishing services provide custom printing and quick service color prints from digital files. Video services include producing video reports and technical videos and capturing presentations of scientific and technical programs. TIS digital video editing equipment allows in-studio and on-location editing. TIS' photoarchivist is digitizing and ingesting all of NRL's historical and recent photos/negatives into an integrated database. The TIS Exhibits Program works with NRL's scientists and engineers to develop exhibits that best represent a broad spectrum of NRL's technologies and promote these technologies to scientific and non-scientific communities at conferences throughout the United States.

Photographer and videographer capture footage for a technical presentation.

Administrative Services

The Administrative Services Branch is responsible for collecting and preserving the documents that comprise NRL's corporate memory. Archival documents include personal papers and correspondence, laboratory notebooks, and work project files — documents that are appraised for their historical or informational value and considered to be permanently valuable. The Branch provides records management services, training, and support for the maintenance of active records, including electronic records, as an important information resource. The Branch is responsible for processing NRL's incoming and outgoing correspondence and provides training and support on correct correspondence formats and practices. The Branch is responsible for NRL's Forms and Reports Management Programs (including designing electronic forms and maintaining a Web site for Lab-wide use of electronic forms), and is responsible for providing NRL postal mail services for first class and accountable mail and for mail pickup and delivery throughout NRL. The Branch also provides NRL Locator Service.



Employees of the Administrative Services Branch working in the Forms/Reports Unit.

Ruth H. Hooker Research Library

NRL's Ruth H. Hooker Research Library continues to support NRL and ONR scientists in conducting their research by making a comprehensive collection of the most relevant scholarly information available and useable; by providing direct reference and research support; by capturing and organizing the NRL research portfolio; and by creating, customizing, and deploying a state-of-the-art digital library.

Print and digital library resources include extensive technical report, book, and journal collections dating back to the 1800s housed within a centrally located research facility that is staffed by subject specialists and information professionals. The collections include 50,000 books; 54,000 digital books; 115,000 bound historical journal volumes; more than 3,500 current journal subscriptions; and approximately 2 million technical reports in paper, microfiche, or digital format (classified and unclassified). Research Library staff members provide advanced information consulting; literature searches against all major online databases including classified databases; circulation of materials from the collection including classified literature up to the SECRET level; and retrieval of articles, reports, proceedings, or documents from almost any source around the world. Staff members provide scheduled and on-demand training to help researchers improve productivity through effective use of the library's resources and services.

The Research Library staff has developed and is continuing to expand the NRL Digital Library. The Digital Library currently provides desktop access to thousands of journals, books, and reference sources to NRL-DC, NRL-Stennis, NRL-Monterey, and the Office of Naval Research.

Library systems provide immediate access to scholarly information, including current and archival journals, trade magazines, and conference proceedings that are fully searchable at the researcher's desktop (more than 15,400 titles). Extensive journal archives from all the major scientific publishers and scholarly societies are now available online. The breadth and depth of content available through TORPEDO, NRL's locally loaded digital repository, continues to grow and provides a single point of access to scholarly information by providing full text search against journals, books, conference proceedings, and technical reports from 20 publishers (15.7 million items by May 1, 2016). The NRL Online Bibliography, a Web-based publications information system, is ensuring that the entire research portfolio of written knowledge from all NRL scientists and engineers since the 1920s will be captured, retained, measured, and shared with current and future generations.

Librarians working in the Ruth H. Hooker Research Library.

OTHER RESEARCH SITES

NRL has acquired or made arrangements over the years to use a number of major sites and facilities outside of Washington, D.C., for research. The largest facility is located at Stennis Space Center (NRL-SSC) near Bay St. Louis, Mississippi. Others include a facility near the Naval Postgraduate School in Monterey, California (NRL-MRY), and the Chesapeake Bay Detachment (CBD) and Scientific Development Squadron ONE (VXS-1) in Maryland. Additional sites are located in Virginia, Alabama, and Florida.

Stennis Space Center (NRL-SSC)

NRL at John C. Stennis Space Center, Mississippi (NRL-SSC), consists of NRL's Oceanography Division and portions of the Acoustics and Marine Geosciences Divisions. NRL-SSC, a tenant at NASA's John C. Stennis Space Center (SSC), is located in the southwest corner of Mississippi, about 40 miles northeast of New Orleans, Louisiana, and 20 miles from the Mississippi Gulf Coast. NRL-SSC personnel have been located at SSC since the early 1970s, when they were part of the Navy Ocean Research and Development Activity and, later, the Navy Oceanographic and Atmospheric Research Laboratory before consolidating with NRL. Other Navy tenants at SSC include the Commander, Naval Meteorology and Oceanography Command (CNMOC), the Naval Oceanographic Office (NAVOCEANO), Naval Oceanography Operations Command, Naval Small Craft Instruction and Technical Training School, Special Boat Team Twenty-Two, a regional Navy Office of Civilian Human Resources, and numerous other Navy commands. Other federal and state agencies at SSC involved in marine-related science and technology include NASA, elements of the National Oceanic and Atmospheric Administration (NOAA), U.S. Geological Survey, the Environmental Protection Agency, the Center of Higher Learning, University of Southern Mississippi Department of Marine Science, and Mississippi State University.

Vertical microstructure profiler.

Collocation NRL with such a diverse range of federal, state and private organizations allows for excellent collaborative partnerships. NRL-SSC especially benefits from the collocation of CNMOC and NAVOCEANO, which are major operational users of the oceanographic, acoustic, and geosciences technology developed by NRL-SSC researchers.

NAVOCEANO operates the Navy DoD Supercomputing Resource Center (DSRC) also located at SSC. One of the nation's High Performance Computing Centers, the Navy DSRC provides operational support to the warfighter and access to NRL for ocean and atmospheric modeling efforts. NAVOCEANO also operates the Maury Library, which has the largest oceanography collection of its kind in the world. The Acoustics branch (Code 7180), Marine Geosciences and Oceanography Divisions occupy more than 155,000 ft^2 of research, computation, laboratory, administrative, and warehouse space. Facilities include the sediment core laboratory, transmission electron microscope, moving-map composer facility, underwater navigation control laboratory, computed tomography scanning laboratory, real-time ocean observations and forecast facility, ocean color data receipt and processing facility, environmental microscopy facility, maintenance and calibration systems, Ocean Dynamics and Prediction Computational Network Facility, and numerous laboratories for acoustic, geosciences, and oceanographic computation, instrumentation, analysis, and testing. Special areas are available for constructing, staging, refurbishing, and storing seagoing equipment.

John C. Stennis Space Center, Mississippi (NRL-SSC).

Monterey (NRL-MRY)

The NRL Monterey detachment (NRL-MRY) is located in Monterey, California, on a 5-acre Annex about one mile from the Naval Support Activity, Monterey (NSAM) main base and the Naval Postgraduate

NRL Monterey's 15,000 ft^2 Marine Meteorology Center. The building was dedicated in October 2012.

School (NPS) campus. The Marine Meteorology Division has occupied this site since the early 1970s, when the U.S. Navy collocated its meteorological research facility with the operational center, Fleet Numerical Meteorology and Oceanography Center (FNMOC). This collocation of research, education, and operations continues to be a winning formula. FNMOC remains the primary customer for the numerical weather prediction and satellite product systems developed by NRL-MRY. NRL-MRY scientists have direct access to FNMOC's supercomputers, allowing advanced development using the real-time, on-site, global atmospheric and oceanographic databases, in the same computational environment as operations. Such access offers unique advantages for successfully implementing new systems and system upgrades and allows for rapid integration of new research results into the operational systems. NRL-MRY occupies two out of the five primary buildings on the Annex with a total floor space of approximately 40,000 ft^2. One of the buildings, the Marine Meteorology Center, was completed and dedicated in October 2012 and houses the atmospheric aerosol laboratory, computer facility, the Meteorology Applications Development Branch, and the Division's front office suite. A configurable, cutting-edge aerosol and radiation measuring and observation platform is situated on the roof of the building for long-term monitoring of the air quality in Monterey, complementing the standard meteorological observation suite of the National Weather Service Forecast Office for San Francisco/Monterey Bay, collocated in the Annex. NRL-MRY acquires approximately 3 TB of global satellite data daily and, using state-of-the-art processing software, produces approximately 100,000 imagery products per day in near real time for distribution on its public and classified web pages. A new generation of geostationary satellite sensors will allow end users to see weather events on a spatial and temporal scale not previously available. NRL-MRY has added a ground station on site for collection of data from the new generation of GOES (U.S.) geostationary satellites, allowing real-time data processing of these sensor data and providing imagery for improved observational analysis and weather forecasts.

Chesapeake Bay Detachment (CBD)

NRL's Chesapeake Bay Detachment (CBD) occupies a 168-acre site near Chesapeake Beach, Maryland, and provides facilities and support services for research in radar, electronic warfare, optical devices, materials, communications, and fire research.

Because of its location high above the western shore of the Chesapeake Bay, unique experiments can be performed in conjunction with the Tilghman Island site, 16 km across the bay from CBD. Some of these experiments include low-clutter and generally low-background radar measurements. Using CBD's support vessels, experiments are performed that involve dispensing chaff over water and characterizing aircraft and ship radar targets. Basic research is also conducted in radar antenna properties, testing of radar remote sensing concepts, use of radar to sense ocean waves, and laser propagation. A ship motion simulator (SMS) that can handle up to 12,000 lb of electronic systems is used to test and evaluate radar, satellite communications, and line-of-sight RF communications systems under dynamic conditions (various sea states).

CBD's LCM-8 providing test support for electronic warfare research.

CBD also hosts facilities of the Navy Technology Center for Safety and Survivability that are primarily dedicated to conducting experimental studies related to all aspects of shipboard safety, particularly related to flight decks, submarines, and interior ship conflagrations. The Center has a variety of specialized facilities including two fully instrumented real-scale fire research chambers for testing small (28 m^3) and large (300 m^3) volume machinery spaces, a gas turbine engine enclosure and flammable liquid storeroom fire suppression systems; three test chambers (0.3, 5, and 324 m^3) for conducting experiments up to 6 atmospheres of pressure; a 50 ft × 50 ft fire test chamber fitted with a large-scale calorimeter hood rated up to 3 MW; a 10,000 ft^2 mini-deck that affords capabilities for studying characteristics and suppression of flight deck fires and suppression techniques; two mobile instrument vans for remote field tests support; and an LCAC gas turbine engine module. The 5 m^3 chamber was upgraded with new instrumentation and equipment to study cell-to-cell failure propagation in lithium-ion batteries. These upgrades include high-speed visible and infrared cameras, a Fourier transform infrared (FTIR) spectrometer for in situ, real-time chemical species identification, temperature, pressure, and heat flux measurements, and remote, real-time nondispersive infrared (NDIR) monitoring of selected chemical species.

The Radar Range facility at CBD, together with the Maritime Navigation Radar (MNR) Test Range at Tilghman Island, provide the emitters and analysis tools for developing comprehensive maritime domain awareness capabilities. The MNR consists of dozens of radars that represent a precise cross section of today's actual MNR environment. An integrated suite of advanced sensors has been developed for data collection and processing to identify and classify vessels. A suite of similar sensors and processors has been integrated into a transportable shelter, the Modular Sensor System, that can be rapidly deployed to ports or other sites for enhanced maritime awareness reporting.

Scientific Development Squadron ONE (VXS-1)

Scientific Development Squadron ONE (VXS-1), located at Naval Air Station (NAS) Patuxent River, Maryland, is manned by 11 Naval Officers, 54 Enlisted Sailors, and three government civilians. VXS-1 provides airborne science and technology (S&T) research platforms to support Naval Research Laboratory (NRL) and Office of Naval Research (ONR) projects. VXS-1 is the sole airborne S&T squadron in the U.S. Navy and conducts scientific research and advanced technological development for the Department of Defense, the

RC-12M.

Department of the Navy, Naval Air Systems Command (NAVAIR), and many other governmental and nongovernmental agencies. VXS-1 operates and maintains three NP-3 and one RC-12 research aircraft. In addition, the squadron serves as the Aircraft Reporting Custodian (ARC) for nine ScanEagle Unmanned Aircraft Systems (UAS) and the U.S. Navy's only manned airship, the MZ-3A. VXS-1 routinely conducts a wide variety of S&T missions from remote detachment sites around the globe. In 2015, the squadron completed research detachments to U.S. Air Force Forward Operating Location, Curacao; Marine Corps Air Station Kaneohe Bay, Hawaii; Cooperative Security Location Comalapa, El Salvador; NAS North Island, California; NAS Point Mugu, California; and Barrow, Alaska. The squadron has provided flight support for numerous diverse research programs: ONR Code 31's ROUGH WIDOW system, focused on systems integration, sensor fusion, and performance testing of systems in operational maritime patrol environments; ONR's PMR-51 GAMERA sensor development and testing; NAVAIR Code 4.6's UAS Operator Spatial/Situational Awareness Project testing; NAVAIR's Project MORGAN

NP-3C Orion.

testing; NAVAIR's Advanced Project Division's OCEAN HARVEST testing; NRL's Common Airborne Situational Awareness (CASA) system development and testing, vital to providing U.S. Navy Seventh Fleet with an electro-optic system to monitor intercepting aircraft maneuvers; and Multiple-Link Common Data Link System (MLCS) testing for NRL's Information Technology Division. The squadron's ongoing contributions to the Naval Research Enterprise now total over 73,000 flight hours spanning 54 years of Class "A" mishap-free operations.

Midway Research Center

The Midway Research Center (MRC) is a worldwide test range that provides accurate, known signals as standards for performance verification, validation, calibration, and anomaly resolution. In this role, the MRC ensures the availability of responsive and coordinated scheduling, transmission, measurement, and reporting of accurate and repeatable signals. The MRC, under the auspices of NRL's Naval Center for Space Technology, provides NRL with state-of-the-art facilities dedicated to Naval communications, navigation, and basic research. The headquarters and primary site is located on 162 acres in Stafford County, Virginia. The main site consists of three 18.2 m, radome-enclosed, precision tracking antennas and a variety of smaller antennas. The MRC has the capability to transmit precision test signals with multiple modulation types. Its normal configuration is transmit but can be configured to receive as required. The MRC also provides cross-mission and cross-platform services from worldwide locations using a combination of fixed and transportable resources and a quick-reaction, unique signals capability. Assets include Pulstar Systems (several worldwide locations), a 45 m tracking antenna in Palo Alto, California, and a 25 m tracking antenna system on Guam. The MRC instrumentation suite includes nanosecond-level time reference to the U.S. Naval Observatory, precision frequency standards, accurate RF and microwave power measurement instrumentation, and precision tracking methodologies. The MRC also contains an Optical Test Facility with two specialized suites of equipment: a multipurpose Transportable Research Telescope (TRTEL) used for air-to-ground optical communications and for passive satellite tracking operations, and a satellite laser ranging system built around a 1 m telescope as a tool for improving customer ephemeris validation processes.

Midway Research Center facility in Stafford, Virginia.

Pomonkey Facility

The Naval Research Laboratory's Pomonkey Facility is a field laboratory with a variety of ground-based antenna systems designed to support research and development of space-based platforms. Located 25 miles south of Washington, D.C., the facility sits on approximately 140 acres of NRL-owned land, which protect its systems from encroaching ground-based interferers. Among its various precision tracking antennas, the facility hosts the largest high-speed tracking antenna in the United States. Boasting a diameter of 30 m, its range of trackable platforms includes those in low Earth orbit through those designed for deep space missions. The facility's antenna systems are capable of supporting missions at radio frequencies from 50 MHz through 20 GHz and can be easily configured to meet a variety of mission requirements. The ease of system configuration is due to the facility's stock of multiple antenna feeds, amplifiers, and downconverters. Other facility assets include an in-house ability to design, fabricate, test, and implement a variety of radio frequency components and systems. The facility also hosts a suite of spectrum analysis instrumentation that, when coupled to its antenna systems, provides a unique platform for a variety of research and development missions.

The NRL Pomonkey Facility.

Blossom Point Tracking Facility

The Blossom Point Tracking Facility (BPTF) provides engineering and operational support to several complex space systems for the Navy and other sponsors. BPTF is the nation's first satellite command and control facility, established in 1956. The station is situated on the Potomac River shore, approximately 40 miles south of Washington, D.C. A 600 meter buffer zone surrounds the facility's occupied 42 acres of land used by NRL through a land use agreement with the U.S. Army. The site consists of 10 antennas capable of providing simultaneous tracking and data acquisition, health and status monitoring, and command and control in UHF, L, S, C, X, USB, and SGLS bands. Blossom Point Tracking Facility is a highly automated facility able to support both operational and experimental spacecraft. The facility fully supports all spacecraft from concept definition and design to flight operations within the orbits of LEO, MEO, HEO, and GEO. In addition, BPTF is dedicated as a Mission Operations Center (MOC)/Satellite Operations Center (SOC) supporting interfaces to the Air Force Satellite Control Network (AFSCN). An experienced team of industry and government members provides the expertise to oversee space system operations for the life of the spacecraft. The shared and autonomous infrastructures reduce mission operational and management costs, providing value to a wide array of potential customers. As a key member of the NRL Space Systems Development Department, Blossom Point Tracking Facility provides prelaunch, launch, and post-launch support, flight operations, and mission data processing.

Blossom Point Tracking Facility.

Marine Corrosion Facility

The Chemistry Division's Marine Corrosion Facility (MCF) located in Key West, Florida, is a tenant command to the Naval Air Station, Key West on its Trumbo Point Annex. The site offers a "blue" ocean environment with natural seawater characterized by historically small compositional variation and a stable biomass. This continuous source of stable, natural seawater provides a site ideally suited for studies of marine environmental effects on materials, including accelerated and long-term exposure testing and materials evaluation.

The MCF began as a small field exposure site for NRL in the late 1960s, encompassing only a small office and outdoor laboratory on shared facilities. The MCF was staffed full time by NRL researchers starting in 1986 and has experienced significant growth since; today, the MCF includes several buildings on a 4-acre site. The major facilities include a Marine Coatings Application and Test Facility, a high temperature corrosion laboratory, a corrosion fatigue laboratory, a Full-Scale Shaft Bearing Test Facility, a Ballast Water Treatment System Evaluation Facility and associated marine biology laboratory, a 20,000 ft^2 atmospheric test site, once-through natural seawater exposure troughs, and the Navy's only Cathodic Protection Physical Scale Modeling (CP-PSM) Design Facility. The CP-PSM provides a highly accurate capability to physically model the electrochemical behavior of ship hulls and outboard structures to understand both the characteristics and adequacy of corrosion control systems and their relation to underwater electromagnetic fields. The CP-PSM has been the cornerstone to Navy impressed current cathodic protection systems, providing new construction design requirements for NAVSEA Program Executive Offices and Allied navies. The MCF's newest capability coming on line in 2017 is the Center for Corrosion and Atmospheric Structural Testing (C-COAST). The C-COAST facility is a DoD unique test capability that enables atmospheric corrosion testing in a tropical marine environment with the ability to apply static and dynamic structural loads to the articles in test. The C-COAST will have the capacity to test at the coupon level, subsystems, and all the way up to full systems.

NRL's Marine Corrosion Facility in Key West, FL.

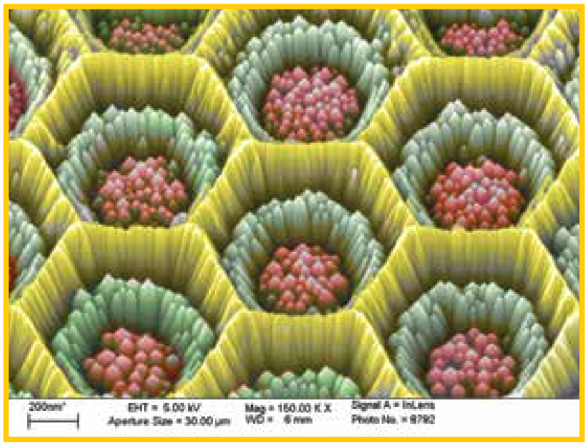
The MCF maintains extensive capabilities for RDT&E of marine engineering and coatings technologies and supports a wide array of Navy and industrial sponsors. Equipment is available for experiments involving accelerated corrosion and weathering, general corrosion, long-term immersion and alternate immersion, fouling, electrochemical phenomena, coatings application and characterization, ballast water treatment, marine biology, and corrosion monitoring. In 2009, the facility received a comprehensive refurbishment due to hurricane damage.

Ex-USS *Shadwell* Research Platform

The Navy Technology Center for Safety and Survivability has a full-scale test ship, the ex-USS *Shadwell* located at the Joint Maritime Test Detachment (JMTD), Little Sand Island, Mobile, Alabama. *Shadwell* is a 457 ft, 9000 ton dock landing ship (LSD). All ship systems germane to damage control are maintained, including heating and air conditioning (HVAC), smoke ejection system (SES), one complete Collective Protection System (CPS) (replicating zone two of the DDG 51 class ships), and electrical, lighting, and internal communication systems (including wire-free and WLAN communications). Specialized test areas include a hangar bay, flight deck with helicopter mockup, submarine test area, machinery space, shipboard magazine including a peripheral vertical launching system (PVLS) magazine, and well deck/vehicle stowage areas. Three damage control lockers are also maintained. The data are collected and displayed via a blown fiber gigabit network that is distributed throughout the ship. In addition, Little Sand Island has a wave tank that is used for in situ burn tests and studies for oil spill containment.

NRL SCIENCE AS ART CONTEST

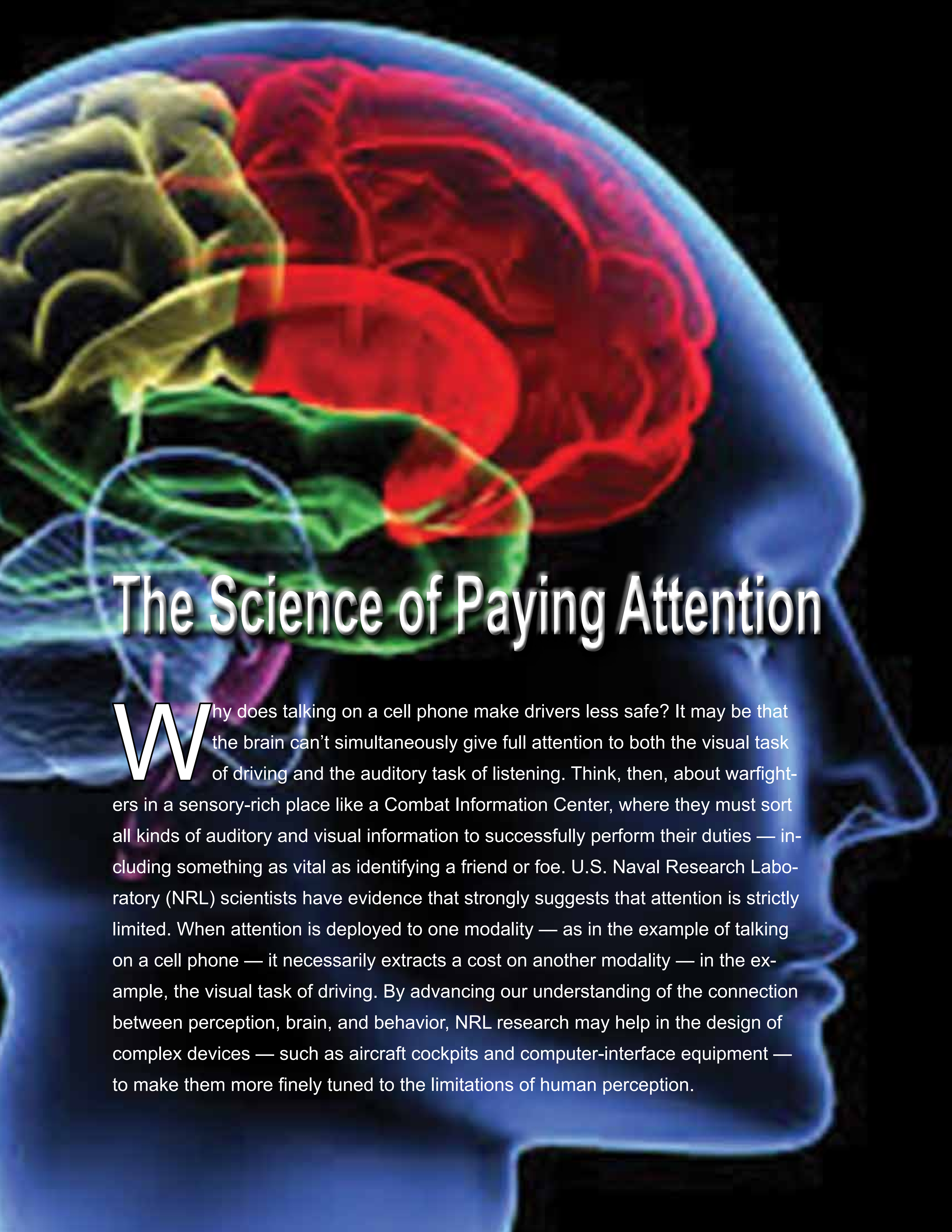
NRL Employee Choice



Nano-size Flower

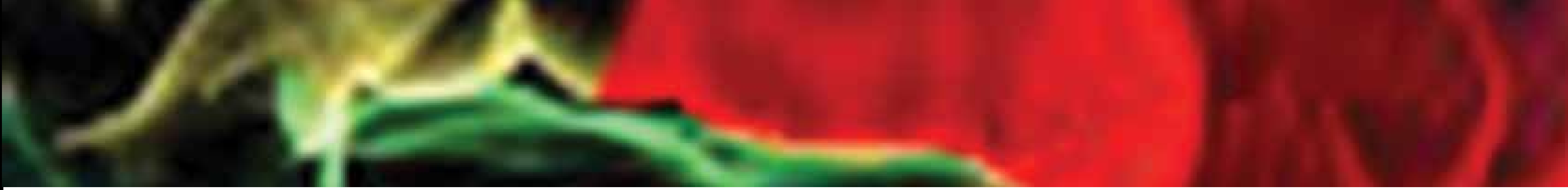
Quantum electronics researchers in the NRL Optical Sciences Division used electron beam lithography to fabricate about 14 million nanoscale "flowers." The flowers shown in this scanning electron microscope image are only 800 nanometers wide — about 75 times smaller than the diameter of a human hair. The flowers are actually photonic crystals generated during calibrations of an interband cascade laser patented by the researchers. The photonic-crystal pattern was transferred to the laser surface by using a nickel mask to etch the center of each flower with ionized chlorine molecules in a high-vacuum chamber. The green and pink (false color) features inside each flower are from micro-masking by the nickel in the calibration sample. Findings published in 2006 in the journal *Applied Physics Letters* describe how the pattern of nanoscale photonic crystals demonstrates single-mode lasing.

Chul Soo Kim
Optical Sciences Division



The Science of Paying Attention

Why does talking on a cell phone make drivers less safe? It may be that the brain can't simultaneously give full attention to both the visual task of driving and the auditory task of listening. Think, then, about warfighters in a sensory-rich place like a Combat Information Center, where they must sort all kinds of auditory and visual information to successfully perform their duties — including something as vital as identifying a friend or foe. U.S. Naval Research Laboratory (NRL) scientists have evidence that strongly suggests that attention is strictly limited. When attention is deployed to one modality — as in the example of talking on a cell phone — it necessarily extracts a cost on another modality — in the example, the visual task of driving. By advancing our understanding of the connection between perception, brain, and behavior, NRL research may help in the design of complex devices — such as aircraft cockpits and computer-interface equipment — to make them more finely tuned to the limitations of human perception.



Audio-Visual Switching in Multisensory Environments

C. Wasylyshyn and S.N. Blisard
Information Technology Division

The U.S. Navy is investing heavily in the development of human–computer interface concepts for the next generation of ships and submarines. Researchers in the field of human–computer interaction are interested in design technologies that let people interact with computers in novel ways. When designing human–computer interface concepts, it is imperative that human performance limitations are taken into account so that the interface technology is relatively easy to learn and use. Currently, many human–computer interfaces are attentionally demanding and dynamic, incorporating vast amounts of audio and visual information that can come from several sources. In our research, we seek to understand the neuropsychological basis of the cognitive burden associated with switching between audio and visual tasks, especially in information-rich, i.e., attentionally demanding, environments. Our findings could support audio-visual interface solutions to help warfighters deal with the vast information sources needed to perform their duties successfully. To that end, we conducted a series of experiments on how techniques based in neuropsychology can be incorporated into the design of novel display technologies that reduce performance costs, i.e., time, effort, and error, in multisensory environments.

BACKGROUND

Efficiently performing a task in many Naval environments, such as watchstanding in a Command and Control or Combat Information Center, requires close attention to changing conditions. Performing a task often involves making decisions about the location or classification of auditory and visual information. An individual operator's task may involve determining the position (e.g., above or below the horizon) or the identity of an object or event (e.g., friend or foe), or both at the same time. Additionally, different tasks involve auditory and visual components (henceforth called *perceptual modalities*). For example, some tasks may only involve visually scanning a display for a target; others may only involve listening over a radio channel for a call sign, while other more complex tasks may involve rapidly *switching* between looking and listening. Task switching is accomplished when participants intentionally shift their mental resources from performing one task to another. Shifting focused attention from performing one task to another leads to measurable costs in time, effort, and frequency of errors.

So far, we have discussed the different types of tasks (e.g., identification or location-determination) that operators might perform, and we have discussed the idea that different tasks place different modality-specific demands on the operator. Other researchers have determined that switching between auditory and visual tasks introduces performance decrements. Researchers have also demonstrated that alerting human subjects to the type of task they are about to perform helps reduce or eliminate these performance decrements. However, researchers have explored alerting of this kind within a single perceptual modality only. Our research investigated whether or not alerting strategies of the type discussed above could reduce or eliminate performance decrements in complex tasks that require both looking and listening.

Two testable assumptions from the neuropsychological literature guided our design:

1. Switching between tasks in the same perceptual modality may produce larger performance costs than switching between tasks in different modalities.[1] Unique brain areas (auditory cortex and visual cortex) are associated with processing the respective kinds of information (Fig. 1(a)). Each of the two brain areas has a limited capacity for processing information, and tapping the same brain area sequentially could exceed the area's capacity and thus increase the chance for performance decrements or costs (e.g., time, effort, and error, as mentioned above). Therefore, it follows that tapping different areas one after the other (e.g., auditory followed by visual or vice-versa) should reduce performance costs.
2. Different brain areas are thought to be associated with processing different types of tasks.[2] "Where" pathways (shown in blue in Fig. 1(b)) in the auditory and visual cortices are thought to be recruited in tasks involving spatial cognition, or location-determination. "What" pathways

(shown in red in Fig. 1(b)) are recruited for tasks involving classification, or identity-determination. Therefore, it follows that switching between tasks that rely on distinct neural pathways should also reduce performance costs.

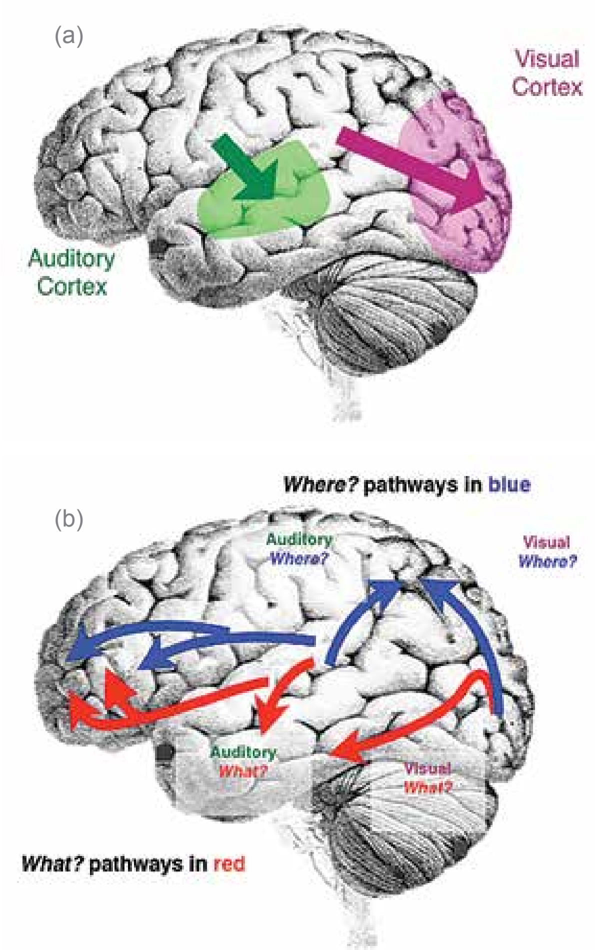


FIGURE 1
(a) Depiction of the human auditory cortex and visual cortex.
(b) Depiction of "Where" and "What" pathways in human auditory and visual cortices.

TECHNICAL APPROACH

Since our study design is relatively complex, we provide the reader with a hypothetical example of a naval operator working in a Combat Information Center:

> Smith, the Tactical Action Officer aboard U.S.S. *Washington*, looks intently at the set of visual displays in front of him, all while wearing a pair of headphones used for monitoring radio communications. The sheer number of visual displays extends beyond his visual field. Additionally, the number of radio channels needing to be monitored outstrips Smith's ability to do so. Luckily for Smith, a new display concept pioneered at the Naval Research Laboratory has been recently installed. Whenever Smith needs to attend to task-relevant information, a cue alerts him to do so. The cue indicates to Smith whether he should focus his attention on listening to his headphones, or on looking at one of his displays, along with indicating to Smith what task he's about to do: determining either the location or type of an unidentified vessel. With Smith's attention being managed by a sequence of alerts, he is able to perform his task effectively and avoid being swamped by information overload.

We created a series of novel experiments that could test the two assumptions described at the end of the previous section. In Fig. 2, we depict the experimental setup, and in Fig. 3, we describe the order in which information was provided to the participants on each trial. Every trial included the presentation of an alert (i.e., a *cue*), followed by the presentation of a target stimulus. The cue was presented either aurally, e.g., giving the word "direction" over headphones to indicate an upcoming location-determination task, or visually, e.g., showing the word "direction" on the visual display. The cue also indicated which task would follow: either a location-determination task (e.g., via seeing or hearing the target stimulus) or an identity-determination task. After each cue and stimulus presentation, a response

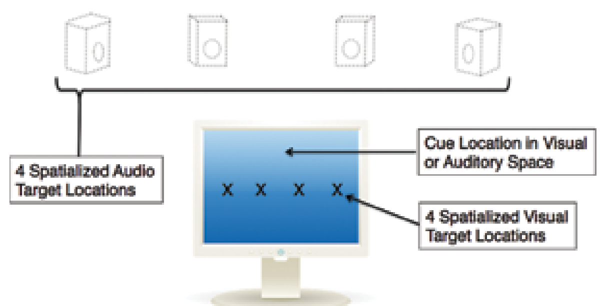


FIGURE 2
The experimental setup included spatialized audio and visual target information. The cue was either heard or seen in the center of audio or visual space.

was made. This design allowed us to measure within-modality costs (performance costs when the perceptual modality of the target stimulus repeats from trial to trial) and across-modality costs (performance costs when the perceptual modality of the target stimulus switches from trial to trial). We manipulated several variables, including cue modality, target modality, and task type ("what" and "where"), and measured several dependent variables — specifically, reaction time for task completion, accuracy, and the associated performance costs.

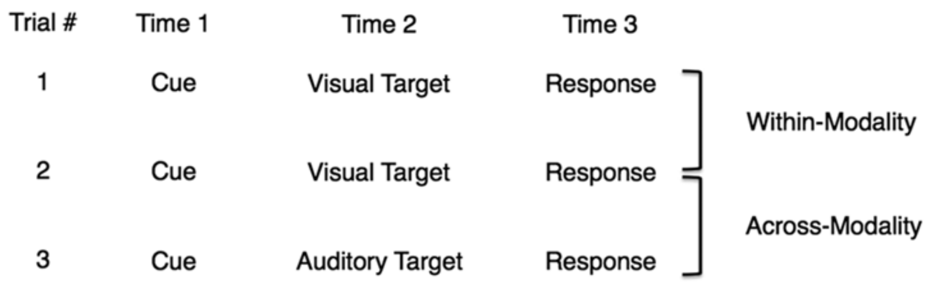


FIGURE 3
Graphic of the types of trials presented and the types of costs measured. The perceptual modality of the cue at Time 1 and the perceptual modality of the target stimulus at Time 2 were manipulated, i.e., the cue at Time 1 and the target stimulus at Time 2 could be either auditory or visual.

EXPERIMENT 1

People typically perform more slowly and less accurately when tasks alternate (switch trials) than when tasks repeat (repeat trials).[3] In our experiments, we asked participants to switch between two types of tasks: "where" and "what" tasks. For the "where" task condition, we asked participants to determine if a target stimulus presented itself on the left or on the right in audio or visual space (Fig. 2). For the "what" condition, we asked subjects to determine if a target stimulus belonged to Category 1 or Category 2.

Results: Confirmation of Neuropsychological Assumption 1

Results from Experiment 1 confirmed our first testable hypothesis. We showed that switching between tasks in the same perceptual modality (i.e., visual to visual or auditory to auditory) was more difficult than switching between tasks in different modalities (i.e., visual to auditory or auditory to visual) in terms of reaction times measured. This result (Fig. 4) was especially prominent when participants were taxed for time, i.e., when they did not have as much time between tasks to prepare for an upcoming trial. In Fig. 4, we show how varying the amount of preparation time participants were given for an upcoming trial (1000 versus 600 milliseconds) affects how long it takes to complete a task when the perceptual modality is the same or different than the preceding task trial, and also whether the benefit that one would obtain from alternating between perceptual modalities is significant.

Results: Confirmation of Neuropsychological Assumption 2

Results from Experiment 1 also confirmed our second hypothesis. We showed that switching between tasks that rely on distinct neural pathways was more efficient than switching between tasks that rely on the same neural pathways. This assumption was tested by comparing two experimental conditions. In the first condition, participants switched between performing a "where" and a "what" task (switching between tasks that employ distinct neural pathways). In the second condition, participants switched between performing two "what" tasks (tasks that rely on the same neural pathways). Not only does alternating between two "what" tasks take significantly longer, but the perfor-

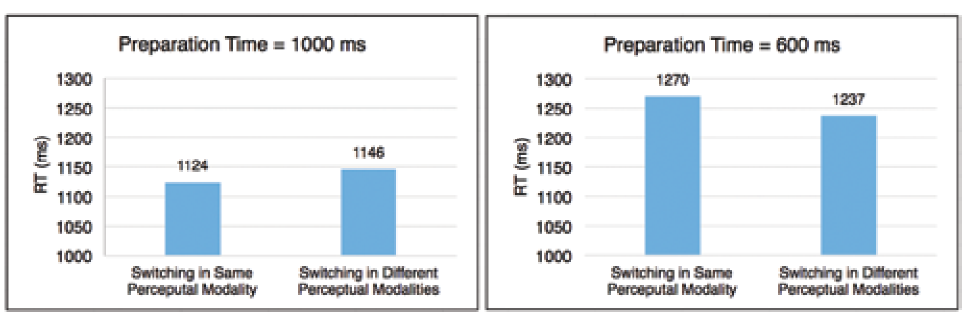


FIGURE 4
Mean reaction times for trials that involve switching in the same perceptual modality versus switching in different perceptual modalities when given 1000 milliseconds to prepare for an upcoming trial (graph on left) or 600 milliseconds to prepare (graph on right). The mean reaction time for switching in different perceptual modalities is significantly faster than switching in the same perceptual modality when given 600 milliseconds to prepare. There are no differences in mean reaction times when given 1000 milliseconds to prepare.

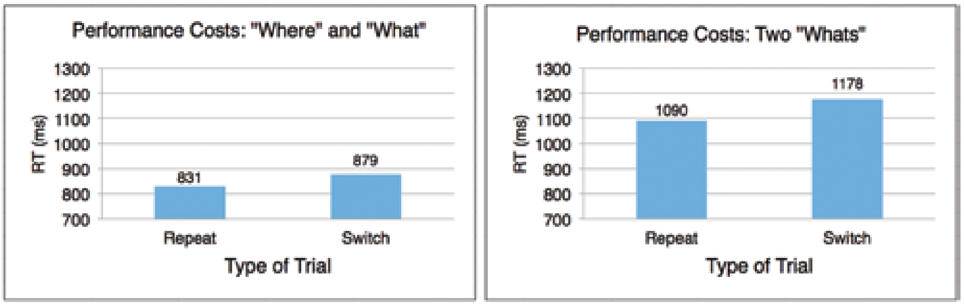


FIGURE 5
Performance costs measured in the two "What" tasks condition (graph on right) and when switching between "Where" and "What" tasks (graph on left).

mance costs involved when switching between "what" tasks on a trial-to-trial basis are also significantly larger (88 milliseconds) than when switching between a "where" and a "what" task (48 milliseconds) (Fig. 5).

Results: Comparing the Two Experimental Conditions

The majority of task switching research focuses on shifting attention between multiple tasks in the same modality (i.e., visual), and specifically on shifting attention between two "what" tasks in the same modality.[3] Our findings are novel because we identified how the two experimental conditions differed. In our study, the type of task completed, how the target task was cued, and the order in which tasks were presented depended on whether the person was switching between two "what" tasks or switching between a "what" and a "where" task. For example, we examined whether the perceptual modality in which the cue was presented interacted with the perceptual modality of the task that the person was switching to. Performance in both conditions (switching between two "what" tasks versus switching between a "what" and a "where" task) was more efficient in responses to visual targets, a phenomenon known as visual dominance. However, while the modality of the cue aided performance when switching between a "what" and a "where" task, in that audio cues were more efficient than visual cues, cue modality did not influence performance when switching between two "what" tasks.

Moreover, an analysis of across-modality costs (see Fig. 3) showed that performance was influenced by the interaction of switching between tasks and switching between perceptual modalities, i.e., participants greatly benefited on trials when the task switched if the sensory modality of the task also switched. In fact, performance costs were eliminated on these types of trials. However, this result only occurred when switching between a "where" and a "what" task; this did not occur when switching between two "what" tasks.

EXPERIMENT 2

Given the differences between the two experimental conditions described above, Experiment 2 focused on examining relationships in audio-visual switching between a "where" and a "what" task in finer detail. In Experiment 1, the modality of the cue, the modality of the target stimulus, and the type of task ("what" and "where") were presented in a random fashion on each trial. We sought to determine whether providing more specific information about upcoming changes in task and/or modality would benefit the operator's performance. Therefore, we varied how information was presented in Experiment 2 by manipulating the predictability (or randomness) of switching for both task and modality and determined how this affected associated performance costs.

Table 1 — The Three Experimental Conditions in Experiment 2. Task Switching and Modality Switching were Manipulated by Condition.

Condition	Task Switching	Modality Switching
1	random	random
2	predictable	random
3	random	predictable

Results from Experiment 2

There were three experimental conditions in Experiment 2 (Table 1). Condition 1 served as a control and was a replication of Experiment 1. In Conditions 2 and 3, the task or the perceptual modality alternated every two trials in a predictable sequence. Participants were made aware of these respective patterns. As expected, we found that participants performed similarly across the conditions at the task level. For example, across Conditions 1 through 3, participants were more efficient in tasks involving visual processing compared to auditory processing (i.e., visual dominance) and for tasks involving decisions about location ("where") compared to tasks involving decisions about classification ("what").

However, while participants performed the tasks in a similar manner, there was a significant difference in performance costs between Condition 1 and Conditions 2 and 3 (Fig. 6). These differences were due to the manipulations of information presentation (i.e., how much, if any, information participants were given about the presentation sequence ahead of completion). There was no significant difference between Conditions 2 and 3, showing that being able to predict upcoming switches in task or modality was not more beneficial to performance in terms of reducing costs.

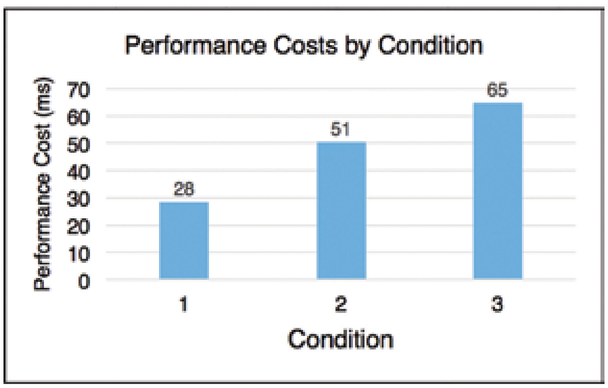


FIGURE 6
Performance costs by condition in Experiment 2.

SUMMARY

Our experimental findings have the potential to inform how multisensory information can be presented in dynamic, attentionally demanding environments. Previous research has investigated cognitively overloaded situations by presenting even more information to the operator in the form of redundancy (i.e., task information is presented in more than one modality and/or format). Rather than augmenting an already information-rich environment with redundant information from other modalities, we sought to determine more efficient ways to present individual alerts within and across modalities. We also sought how to structure the presentation order and the switching of tasks in a way that is more natural to the operator. Having more disposable information at one's fingertips does not always enhance performance, and, in fact, sometimes increases operator performance costs. Incorporating principles from neuropsychology can provide recommendations for designing interfaces in mixed audio-visual Naval environments that take into account human performance limitations.

ACKNOWLEDGMENTS

Thanks to the volunteers at NRL who participated in the collection of this human subject research. Thanks also to Paul Bello for his helpful comments on drafts of this article. This work was supported by Ray Perez in the Office of Naval Research.

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THE AUTHORS

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SAMUEL N. BLISARD holds a B.S. and an M.S. degree in computer science and mathematics from Missouri State University (received in 2000 and 2005, respectively) and a Ph.D. in electrical and computer engineering (received in 2010). He became a Karles Fellow at NRL in 2011. He has been a member of the Navy Center for Applied Research in Artificial Intelligence since 2006. His research interests include modeling human performance with cognitive architectures and human–computer interaction.

MIXING IT UP—

MAKING LIGHT OF MATTER TO CHANGE CHEMISTRY

Light and matter are usually separate and have distinct properties. Now, scientists at the U.S. Naval Research Laboratory have found a way to produce an oscillation between molecules and an optical cavity, creating a mix of the properties of matter and light.

This unusual interaction of matter and light will provide new ways to manipulate the physical and chemical properties of matter. Researchers in the Chemistry Division have accomplished this feat by mixing two sets of oscillations — one from optics, the other from molecules themselves — to adjust the strength or behavior of chemical bonds in certain molecules. Modifications to the chemical behavior were revealed by measured changes in the vibrational frequencies of those bonds.

The mixing — called strong coupling — is part of the work our scientists call quantum optical chemistry. Our research team is exploring the theory of such strong coupling interactions for use in creating chemistry for many U.S. Navy applications, from the protection of personnel to the production of energy.

Manipulating Chemistry through Molecular Vibration–Optical Cavity Coupling

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In the research worlds of chemistry and physics, coupling is an important word. It refers to a kind of interaction that can produce profound outcomes. In quantum physics, the coupling between two oscillators can occur when the two interact through force of attraction to one another. This kind of coupling can be either strong or weak, scientific terms for the energies associated with the coupling — a lot of energy for stronger couplings, less energy for weaker ones. As an everyday illustration of coupling, one may think of two swinging pendulums connected by a spring so that one pendulum, in effect, "feels" the pull or push of the other.

Our U.S. Naval Research Laboratory (NRL) team is interested in the outcomes of strong coupling between an optical cavity and a molecular vibration, which can alter the molecule's vibrational energy. This effect, due to normal mode mixing of the resonances, represents an entirely new method for altering chemical reaction rates and pathways. Similar manipulation of electronic resonances (i.e., excitons) has had a role in enhancing light emission, promoting light detection, enabling lasing, and modifying energy transfer rates. Manipulation of molecular vibrations has gone largely unstudied, even though chemical reactions fundamentally rely on bond breaking and creation. Our early work in this fledgling field has demonstrated coupling — to a range of materials (polymers, ionic-substituted materials, and solutions) — that resulted in significant modification of vibrationally excited populations and kinetics. Investigations into the science of manipulating molecular vibrations through optical coupling could impact the development of chemistries relevant to a diverse host of Naval engineering applications, e.g., organophosphate hydrolysis (toxin remediation for personnel protection), CO oxidation (methanol fuel cells), and vibrationally mediated photo-carrier relaxation (applicable to sensitized photovoltaics for remote energy generation).

TECHNICAL BACKGROUND

Chemists have long sought the holy grail of controlling chemical reactions via bond-specific molecular activation. They have explored this pursuit largely through tailored laser excitation (coherent control, ladder climbing, and wavepacket sculpting), an approach fundamentally limited by a few factors: (1) rapid energy redistribution or dissipation, (2) the requirement that the excited modes involve reactive coordinates and promote progress over activation barriers, and (3) the need for sophisticated laser sources, a factor that greatly restricts ultimate application of this approach.

Our NRL research team is interested in studying how coupling vibrational modes to optical cavities might offer a noninvasive method of systematically and predictably modifying molecular energy landscapes. (Noninvasive, in this context, means that we do not use heat, laser, or another method to stimulate the molecules, and thus the cavity coupling effect is a passive effect that does not require light or any other stimulus.) This research could lead to practical application of specific bond activation, a phenomenon we term *quantum optical chemistry*.

A confined optical mode (e.g., Fabry-Pérot cavity, plasmonic resonance, etc.) that couples to a resonant material transition can produce distinctive results, including enhanced absorption or emission rates, excited-state population control, and, if the interaction is stronger than the relevant dephasing rates, formation of new hybrid states termed *cavity polaritons*. Such strong cavity coupling has been applied to *excitons* to create room temperature Bose-Einstein condensates, climb the Jaynes-Cummings ladder of coupled quantum states, and tailor exciton transfer routes. It has only recently been demonstrated between vibrational resonances and cavities.[1,2,3]

Many ideas and models of strongly coupled electronic states can be extended to vibrations, but there are unique aspects of vibrations that significantly affect their coupling response. Most notably, vibrations reside in an anharmonic potential well, an aspect that produces excited-state transitions red-shifted in energy relative to ground state transitions (Fig. 1(a)). When the polariton state splitting, Ω, is approximately double this red-shift (as for the case described below), the excited-state absorption signals dominate transient measurements, in stark contrast to molecular response outside of a cavity, where the signal strength of excited states is far weaker than for ground state transition. Here, we describe how we create these new polariton states, control their energy positions, and measure the modified molecular states, as well as the implications of our findings for controlling chemistry.

CREATING POLARITON STATES AND TUNING THEIR ENERGIES

Strong coupling between a molecular vibration and optical cavity generates polariton states with mixed vibrational and cavity character. These states (P^+ and P^- in Fig. 1) are separated by the Rabi energy, Ω, and are located above and below the uncoupled modes by half this value (i.e., $\Omega/2$). The transmission spectrum of a strongly coupled system exhibits two transmission bands corresponding to these polaritons (Fig. 1(b)). Such strong coupling may be realized by fabricating a Fabry-Pérot cavity, consisting of the material of interest (e.g., polymer, ionic solution, etc.) sandwiched between two closely spaced Au mirrors. A Fabry-Pérot cavity transmits a narrow resonant band that tunes as a function of interrogation angle. Angle-tuning the cavity sweeps its resonance through that of the molecular vibration, revealing an anti-crossing whose magnitude is the Rabi splitting (shown for a cavity-coupled ionic molecule SCN^- in Fig. 2(a)). The value of Ω, and, therefore, the location of the polariton states, depends on several factors. Most important is the molecular absorptivity, or more specifically, absorption per optical mode volume.

For a molecular load between the two mirrors of a Fabry-Pérot cavity, the coupling strength can be increased by increasing molecular concentration, leading to an approximate square-root dependence, as shown in Fig. 2(b) for a urethane monomer doped into PMMA. (A monomer is a molecule that can be bonded to other molecules to form a polymer. PMMA is short for poly(methyl methacrylate), the transparent plastic sometimes called acrylic glass.) This manipulation has important consequences: (1) Most significantly, the energy positions of these newly formed polariton states may be systematically adjusted to probe their behavior and utilize these new states for modified chemistry. (2) The concentration-dependent optical signature of a molecule has now been converted from the amplitude-domain to the frequency-domain, which has implications for sensing. Instead of monitoring for changes in absorption peak *amplitude* to indicate a sensing event, peak *position*, which in many cases is easier to measure, would indicate a concentration change. (3) Since coupling strength is concentration-dependent, scaling down the optical mode volume allows one to concurrently scale down the absolute number of molecules while maintaining a given concentration. These findings suggest that nanoscale mode volumes, attainable with plasmonic or phonon polariton resonators, could be used to achieve strong coupling among small numbers of molecules.

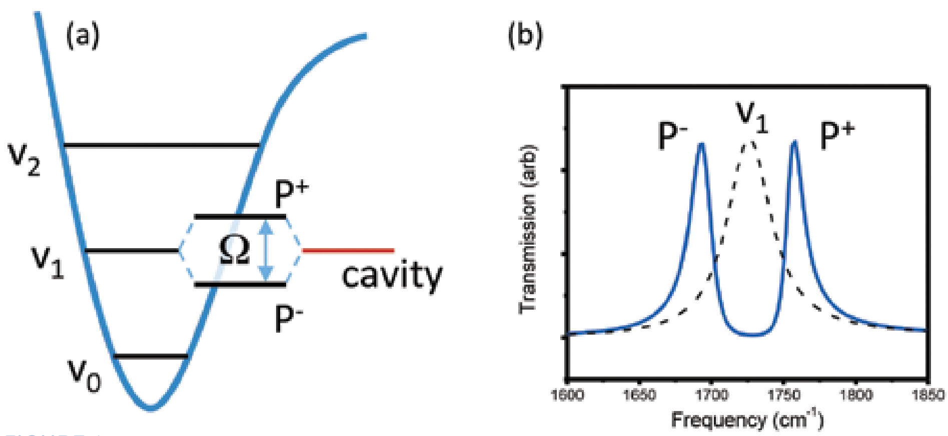

FIGURE 1
(a) Energy diagram of a vibration-cavity polariton system. The uncoupled molecule has a ground vibration level, v_0, and excited vibrational levels v_1, v_2, etc. When the cavity is resonant with a vibrational transition (v_0 to v_1, here), new hybrid polariton modes, P^+ and P^-, are formed. These new states are accessible by the molecule and, as such, may influence excited state kinetics and reactivity. (b) Example transmission spectrum of a Fabry-Pérot cavity tuned to the C-O stretch in PMMA (solid blue curve). Dashed curve is uncoupled resonance position. The two peaks correspond to the polariton modes schematically shown in (a).

MEASURING ALTERED MOLECULAR PROPERTIES

Understanding the dynamics of polaritons in an unreactive system is an important first step in modifying chemical reactivity. We therefore examined excitation and relaxation within the molecular species $W(CO)_6$,

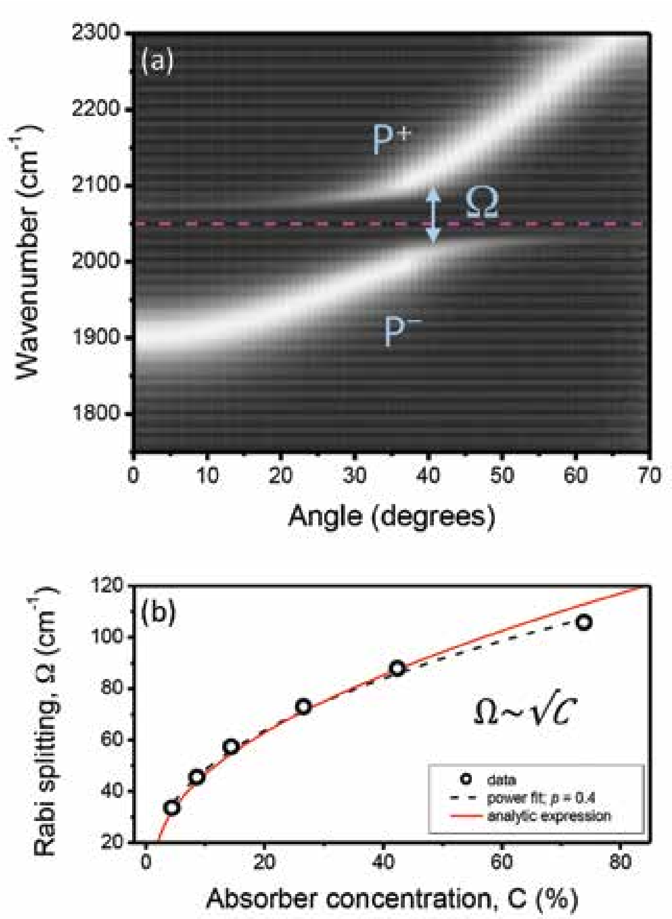

FIGURE 2
(a) Dispersion of cavity-coupled system created by measuring infrared transmission as a function of incident angle. As cavity is angle-tuned through the molecular resonance (~2060 cm^{-1} for SCN^-), an anti-crossing, whose magnitude is the Rabi splitting, Ω, is observed. (b) Ω may be controlled by varying the molecular concentration of a urethane monomer (4,4′-Methylenebis(cyclohexyl isocyanate)) within the cavity.

demonstrating drastically modified relaxation dynamics in a cavity-coupled system influenced by polariton energy and character.

In the pump-probe transient measurements discussed here, incident pump light promotes molecules into excited-states (from v_0 to v_1, v_2, P^+, or P^- in Fig. 1(a)). At some later time, a probe beam interrogates the system. Reduced population in v_0 will cause reduced absorption associated with this transition, while newly populated states will give rise to new absorptive features. These transient absorptions are tracked as a function of time to yield excited-state lifetimes. In conventional systems (i.e., not cavity coupled), transient absorption magnitude is linear with respect to excited-state population, allowing one to directly extract excited-state populations and lifetimes. In cavity-coupled systems, the excited populations are not directly proportional to absorption, and they instead announce themselves as qualitative changes in the transmission spectral shape (e.g., reduced Rabi splitting or additional Rabi splittings at new frequencies). This population-dependent spectral form does not lend itself to straightforward analysis because the entire spectral form may change, but it is well-behaved, and it follows the transmission through a Fabry-Pérot cavity, as described by Eq. (1):

$$T \cong \frac{t^2 e^{-\alpha L}}{1+r^2\, e^{-2\alpha L} - 2re^{-\alpha L}\cos(4\pi n L \nu)} \tag{1}$$

The transmissivity and reflectivity of the mirrors are t and r, α is the absorption of the material in the cavity, L the cavity length, n the optical index, and ν the frequency. Excited-state populations are included as Lorentzian oscillators defining the optical index and absorption functions (n and α). With such a predictive tool in hand, we turn our attention to the test-bed CO stretch of $W(CO)_6$ in hexane. The transmission spectra of cavity-coupled $W(CO)_6$ are calculated for various population distributions (Fig. 3(a)). If only ground-state depletion is included (blue curve in Fig. 3(a)), the

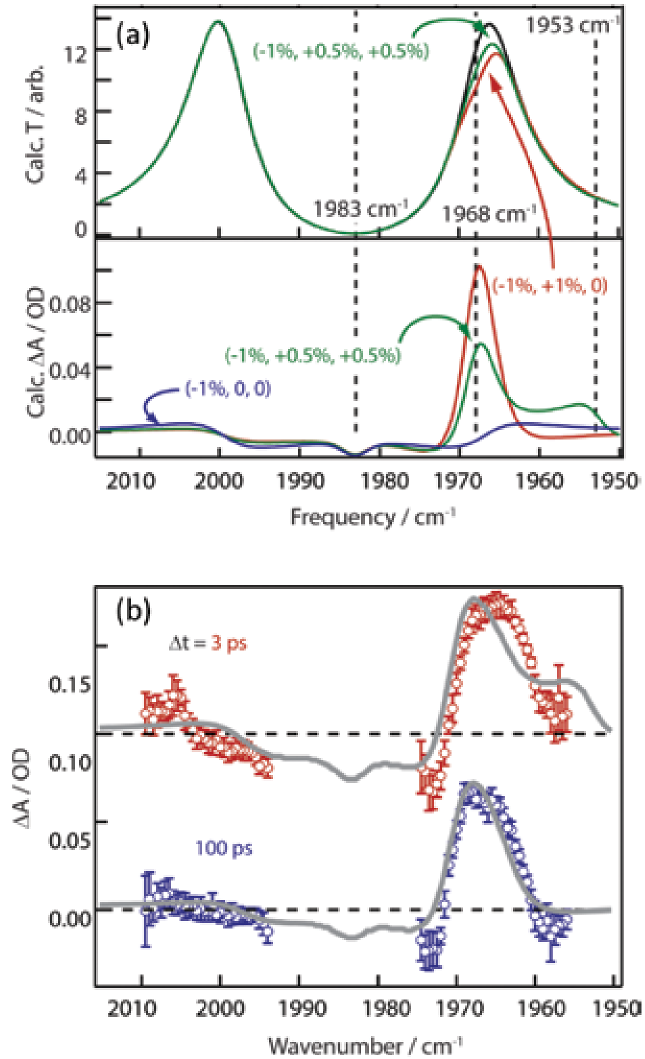

FIGURE 3

(a) Transmission, T, and transient absorption, ΔA, spectra calculated for $W(CO)_6$ using Eq. (1) and assuming various populations in v_0 and two excited states notated as "(Δv_0, Δ excited state 1, Δ excited state 2)". When energy of excited state is ~Ω/2, transient response is dominated by large positive signals near P^- (1968 cm^{-1} in this case). (b) Experimental transient absorption spectra recorded at 3 and 100 ps after excitation, showing qualitatively similar behavior.

transient spectrum is symmetric about the uncoupled resonance position. If the higher excited states or other transitions (e.g., v_1, v_2, P^+, or P^-) are included (red and green curves), large positive features dominate the spectra near the P^- branch (~1968 cm^{-1} in this case). The dominance of these excited-state absorptions occurs because of the coincidence of their anharmonically red-shifted absorptions with the coupling-induced shift of the transmission (by Ω/2), and, as a result, these excitations fall within the P^- window. Notably, the predicted and measured intensities of the transient absorption (Figs. 3(a) and 3(b), respectively) is greatly enhanced over those measured in the uncoupled system. The calculated transient absorption spectra qualitatively match the experimental results (Fig. 3(b)) and can be further applied to time-dependent traces taken at a number of frequencies spanning both P^+ and P^-.

The time-dependent response exhibits two regimes. At early times (<5 ps) coherent excited-state populations oscillate between the coupled modes and are observed as Rabi oscillations (not shown) whose period equals the Rabi splitting energy. Dephasing these oscillations leaves an incoherent population that may reside in the various molecular and polariton states (Fig. 4(a)). The decay of this incoherent population may be tracked by analyzing time-dependent traces taken at several frequencies (Fig. 4(b)). These data are well-described (global fit results shown as black curves)

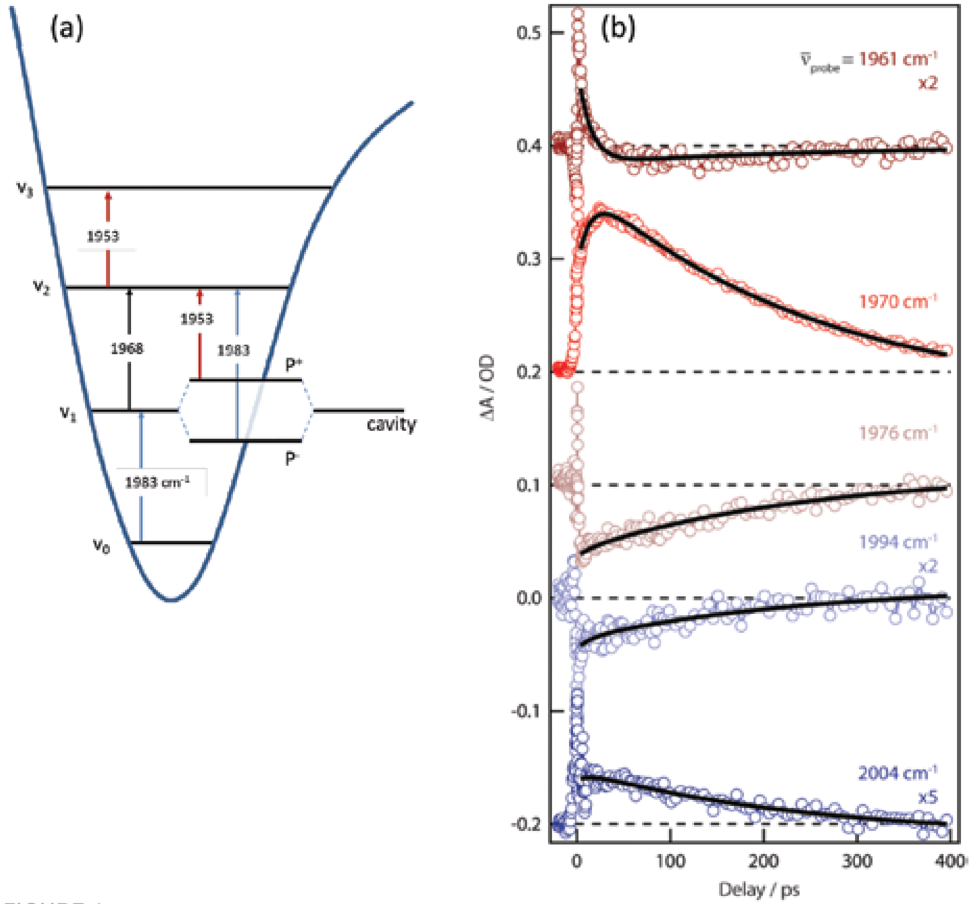

FIGURE 4
(a) Energy diagram for transition identification. While identification of the 1953 cm^{-1} transition is ambiguous, angle-tuning of polaritons will allow us to associate it with P^+ population (see text and Fig. 5).
(b) Transients at several frequencies spanning P^+ and P^-. Global fits are overlaid in black and yield decay dominated by transitions at 1968 and 1953 cm^{-1}.

by only two excited-state populations with decay rates of 14 and 240 ps at energies of 1953 and 1968 cm^{-1}, respectively. The 14 ps decay component is five times faster than the population relaxation observed in the uncoupled molecules, where relaxation times of 70 and 140 ps were found.

IDENTIFICATION OF MODIFIED MOLECULAR STATES

The *slowly* relaxing state at 1968 cm^{-1} is identified as the v_1 population since that is the only transition at that energy (Fig. 4(a)), but there are two possible identities of the transition observed at 1953 cm^{-1}. This frequency is consistent with both P^+ and v_2, but we will tentatively associate this rapidly relaxing state with P^+ population because its relaxation time can be tuned with the incident angle as will be discussed next. This angle-dependent response is expected for a polariton but not a purely vibrational state. Detuning the cavity from optimal coupling has two important effects: (1) it moves the energy positions of the detected polaritons, and (2) it changes the quantum mechanical character of these hybrid modes. Polaritons are quantum-mechanical mixtures of the two coupled states: vibration and cavity photon in this case. The relative fraction of vibration and photon character of a polariton is a function of cavity detuning, with equal proportions occurring at the position of optimal tuning (i.e., minimum polariton separation, which is the Rabi splitting Ω, schematically shown with the blue line in Fig. 5(a)). Polaritons at this point are equal fractions of vibration and cavity photon, and consequently, have a lifetime that is a combination of the two. Detuning the cavity to the red creates an upper polariton (P^+) with greater vibrational character, which should exhibit a longer lifetime, since the uncoupled vibration has longer dephasing and population lifetimes (~9 and 140 ps, respectively) compared to the cavity lifetime (~3 ps). Accordingly, when we measure the decay rate of the fast state as a function of interrogation angle, we find that it becomes slower when the cavity is detuned to the red (Fig. 5(b)). This result supports identification of this population as that of the upper polariton, but the polariton energy also changes

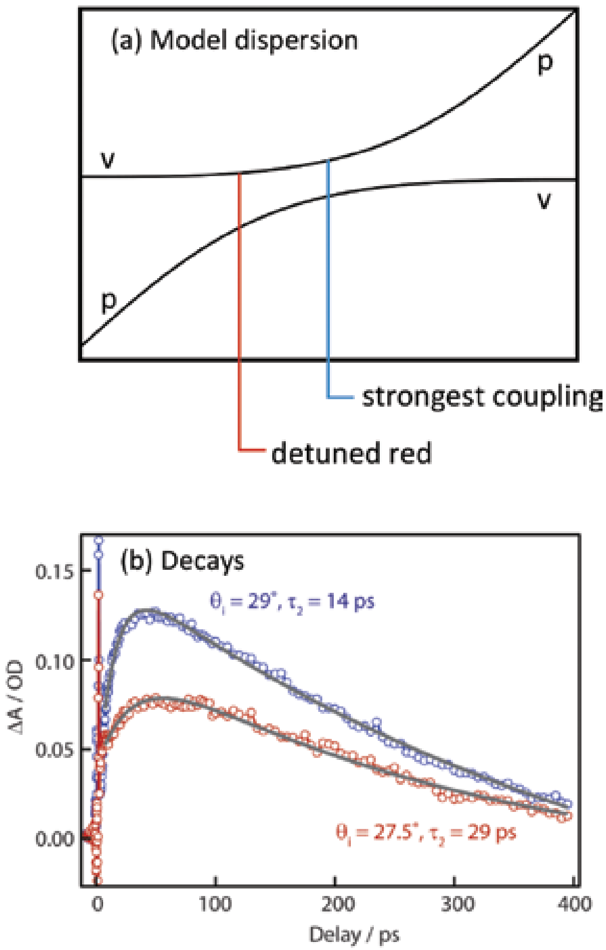

FIGURE 5
(a) Schematic of the modal dispersion illustrating the implication of detuning on polariton position and character. Character of modes is identified with v and p, indicating mostly vibration or photon character. For instance, the upper branch evolves from vibration to photonic character as the cavity is tuned from left to right. (b) Kinetic traces of transient absorption, ΔA, taken for tuned (blue) and red detuned (red) cavities showing increased lifetime correlated with greater vibrational character of the upper branch when red detuned.

with tuning and the decay rates are sensitive to energy differences with acceptor modes.

Though the exact mechanism of lifetime manipulation is currently unknown (either altering energy alignment with acceptor modes or changing the degree of vibrational character of the state), this work opens up the exciting prospect of systematically controlling the excited-state lifetime of polariton states through several methods. One could create vibration-cavity polaritons with varying degree of vibration or photonic character, design a cavity to target a desired photon lifetime, or tailor the alignment between polariton and acceptor modes. These noteworthy results are the first observation of vibration-cavity polariton dynamics and, in fact, the first transient results for any cavity-coupled vibrations.

IMPACT FOR CHEMISTRY

To cause matter to behave in a controlled way has long been a challenge for researchers. We've presented exciting findings that build on recent advances in the understanding of manipulating matter at the smallest scales — including the work of the 2001 Nobel Prize laureates in making atoms "sing in unison." At the same time, our NRL research team has only begun to explore a field of investigation rich with unexplored possibilities. Our work now strives to modify the rate and selectivity of chemical reactions through control of molecular energy states, with the hope that this new method might enable chemical synthesis in ways currently unreachable and perhaps not even yet imagined.

ACKNOWLEDGMENTS

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[Sponsored by the NRL Institute for Nanoscience]

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THE AUTHORS

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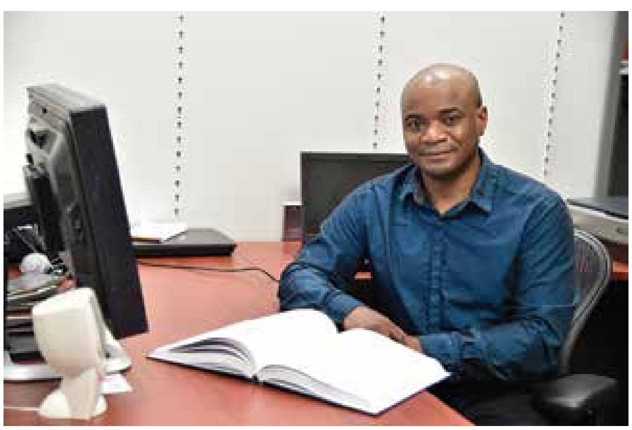
ADAM DUNKELBERGER graduated from the Ohio State University in 2007 with a B.S. degree in chemistry. He earned a Ph.D. in physical chemistry, specializing in vibrationally mediated reaction dynamics, from the University of Wisconsin-Madison in 2013. While in graduate school, he was a Mirzayan Science and Technology Policy Fellow at the National Academies of Science, Engineering, and Medicine. As a National Research Council postdoctoral associate at NRL, he conducts a range of research in ultrafast dynamics, including energy transfer in small molecules, carrier dynamics at plasmon-semiconductor interfaces, and phonon-polariton dynamics in polar dielectrics.



KENAN FEARS is a materials scientist/bioengineer with 10 years of experience in surface analysis of proteins and peptides at solid interfaces and more than 15 years of experience in materials synthesis and characterization. He was an Integrative Graduate Education and Research Traineeship fellow at the Missouri University of Science and Technology (1999–2001), where he received an M.S. degree in ceramic engineering. He was a Graduate Assistance in Areas of National Need fellow at Clemson University (2003–2009), where he earned a Ph.D. in bioengineering. Dr. Fears works in the Chemistry Division, where he completed a postdoctoral fellowship (2009–2012) before becoming a materials research engineer in 2012.

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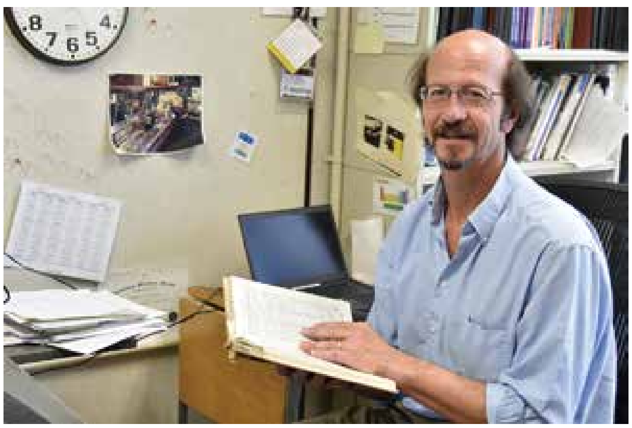

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Plasma aplenty in a place called space

Scientists think that only 1 percent of the matter in our universe is solid, liquid, or gas and 99 percent of the material is plasma. Like a gas, plasma has no definite shape or volume, but, unlike a gas, it responds strongly to electromagnetic forces. People see a plasma on a regular basis without even realizing it, with common examples that include lightning, electric sparks, fluorescent lights, neon lights, plasma televisions, some kinds of flame, and the stars.

The presence of dust in a plasma makes it difficult to study them in a laboratory setting. Dusty plasma, also called complex plasma, contains small, solid charged particles distributed throughout the ionized gas. The reason dusty plasma is worth studying is that the dust particles themselves can become electrically charged, positive or negative, and they have a particle mass and a charge state much larger than an ion-based plasma.

The U.S. Naval Research Laboratory team has designed sophisticated facilities to study dusty plasma systems in space. By carrying out controlled experiments in Earth's ionosphere with charged particle releases, they are learning more about the properties of dusty plasmas. Space is a great place to study dusty plasmas because of the lack of walls. NRL researchers in the Plasma Physics Division have conducted a set of rocket experiments that expands their investigation into the outermost layers of Earth's atmosphere.

Charged Aerosol Release Experiment II (CARE II) and the Investigation of Artificial Dusty Plasmas in the Ionosphere

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The properties of "dusty or dirty plasmas" have been investigated with the release of dust into an electron plasma. Dusty plasmas differ from ordinary electron/ion plasmas because they are composed of positively and negatively charged particulates which have much greater mass than atomic or molecular ions. By carrying out controlled experiments in ground-based laboratories, using plasma wave sensors, charged particle probes, low-light cameras, and electromagnetic wave transmitters and detectors, researchers have shown the formation of ion-dust crystals, the excitation of dust-acoustic waves, and production of large electric fields as the heavy charged particles move across magnetic fields.

The NRL plasma research reaches beyond our laboratory walls. Since 2009, in collaboration with many international and U.S. laboratories and universities, such as the NASA Wallops Flight Center and the coauthor institutions, U.S. Naval Research Laboratory (NRL) has executed a project to use rockets to release dust in the upper atmosphere to form a dusty plasma in space. Known as the Charged Aerosol Release Experiment (CARE), the project has launched two instrumented rockets so far, the first in September 2009 and the second in September 2015. Studying the dusty plasma clouds formed by the rockets gives us a wealth of data for better understanding how particulates and molecule clouds from jets, rocket exhaust, and explosions impact Earth's atmosphere.

CARE I SOLID ROCKET MOTOR EXPERIMENT

Rockets burning in the upper atmosphere produce exhaust that can impact the ionosphere. The CARE program is designed to make observations of such disturbances from solid rocket motors. To accomplish this task, the first CARE project employed a sounding rocket to carry both a chemical release module and a radio beacon instrument into the bottom of the ionosphere. CARE I was supported by ground-based measurement instruments such as radio wave receivers and cameras.

The rocket for the CARE I mission — launched in September 2009 — was configured as a Black Brant XII with the Nikha motor used as the chemical payload to inject dust and molecules into the upper atmosphere. The motor produces 111 kg of aluminum oxide particulates and 200 kg of solid rocket motor exhaust.

Radar and optical sensors observed a supersonic dust cloud released from a sounding rocket into the upper atmosphere. Ground radars as well as optical and radio beacon receivers operating along the Mid-Atlantic Coast and on Bermuda monitored impact of the solid rocket exhaust on the ionosphere.[1] Ground optical systems showed both (1) sunlight scattered from the aluminum oxide (Al_2O_3) particulates and (2) light emissions from atomic oxygen associated with charge exchange of exhaust molecules (H_2, H_2O, CO_2) in the ionosphere, followed by oxygen excitation from electron-ion recombination. The initial CARE I exhaust particles formed a cone that evolved into a ring because of spin of the rocket payload. The red-line emission from atomic oxygen resulted from oxygen ion charge exchange, followed by recombination excitation.

CARE II MULTIPLE ROCKET MOTORS EXPERIMENT

As a follow-on to CARE I, CARE II mission was launched from Andøya, Norway, in September 2015. The primary objective of the second CARE mission was to study hypersonic expansion of dust and molecular clouds in the presence of an ambient plasma (the ionosphere). This flight had a full set of plasma diagnostics to measure the charged dust density, the electron and ion densities, and the electrical fields associated with plasma waves produced by the release (Fig. 1). The chemical release payload was upgraded to use multiple rocket motors that release about 100 kg of dust in 2 seconds, not the 17.8 seconds of CARE I.

FIGURE 1
CARE II rocket payload consisted of three sections. The rocket used 37 Canadian Rocket Vehicle 7 (CRV7) motors fired simultaneously to inject dust particles into the ionosphere. The CRV7 is a folding-fin ground attack rocket used in helicopter munitions, and its motor is designed by Magellan/Bristol Aerospace. Chosen for the short 2-second burn time and large 2 km/s exit velocity, the motors were ignited on the downleg of the sounding rocket trajectory, with the motor exit ports pointed up. The exit ports on the motors were designed to produce a wide dispersion of the exhaust material. (WFF = NASA Wallops Flight Facility.)

With these improvements, a denser dust cloud could be formed, increasing the chances of detecting enhanced radar scatter. The in situ electric field measurements were added to determine the sources for the observed plasma waves excited by rocket engines operating in the ionosphere. The CARE II payload trajectory and velocity profiles are illustrated in Fig. 2. The rocket motor payload on CARE II was a good representation of commonly used solid rocket motors that fire in the ionosphere.

The CARE II rocket fired 37 rocket motors simultaneously to inject 66 kg of dust particles in the upper atmosphere at an altitude of 266 km (approximately 165 miles above Earth). The dust, composed of aluminum oxide particulates, was accompanied by 130 kg of molecules such as carbon dioxide, water vapor, and hydrogen. The large concentration of dust and exhaust material interacted with the ionosphere to produce dusty plasma with high-speed "pickup ions," a technical term for ionized or electrically charged (positive or negative) particles. The launch occurred just after sunset to place the dust particles in sunlight for easy viewing by cameras in darkness from an airplane flying above the clouds. A Sony Alpha-7 digital camera was used on board a Beechcraft B200 airplane to photograph sunlight scattered from the expanding dust cloud, and the captured images show a dispersal of the dust that appears almost spherical (Fig. 3).

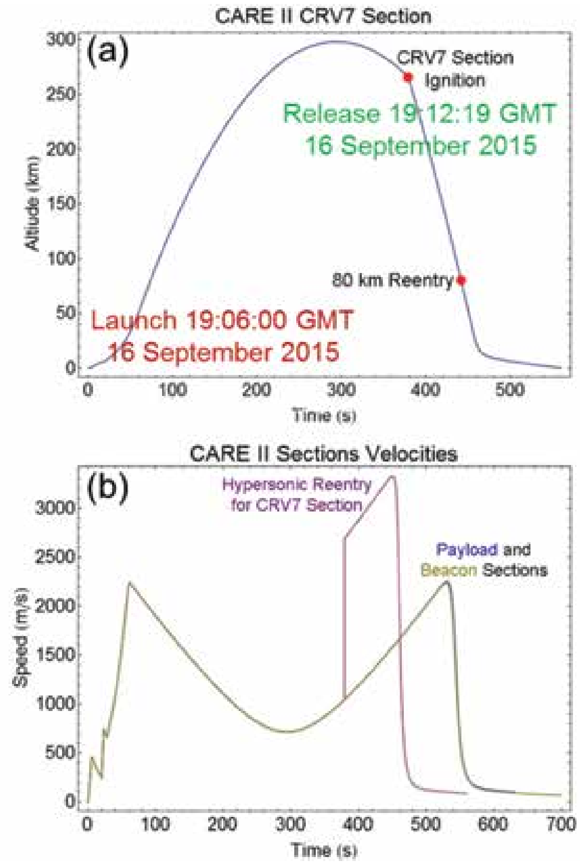

FIGURE 2
CARE II trajectory of (a) the CRV7 chemical release section and (b) the acceleration of the payload, chemical, and beacon sections.

MEASUREMENTS AND OBSERVATIONS OF THE CARE II PLASMA CLOUD

The electric field instrument on the CARE II rocket functioned as both a plasma wave sensor and fluctuation monitor (Fig. 4). The instrument sensitivity was better than 100 μV/m and with a frequency range extending above 10 kHz. These parameters were chosen to cover both low frequency waves from the dust and magnetohydrodynamic (MHD) components and higher frequency waves associated with ion acoustic fluctuations. The instrument used a 32 ks/s sampling rate with a 12-bit analog-to-digital converter. The individual samples shown in Fig. 5 were from eight separate

FIGURE 3
White light camera images of the CARE II dust release with a 30-degree field of view at a range of 563 km.

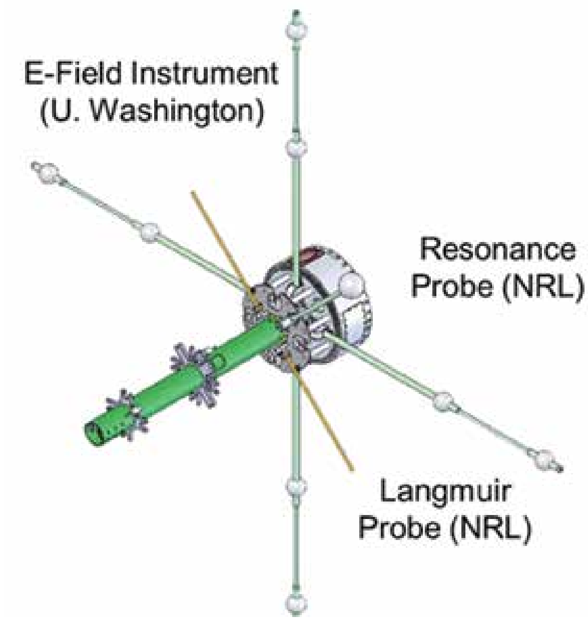

FIGURE 4
E-field and plasma probe instruments flown on the CARE II mission.

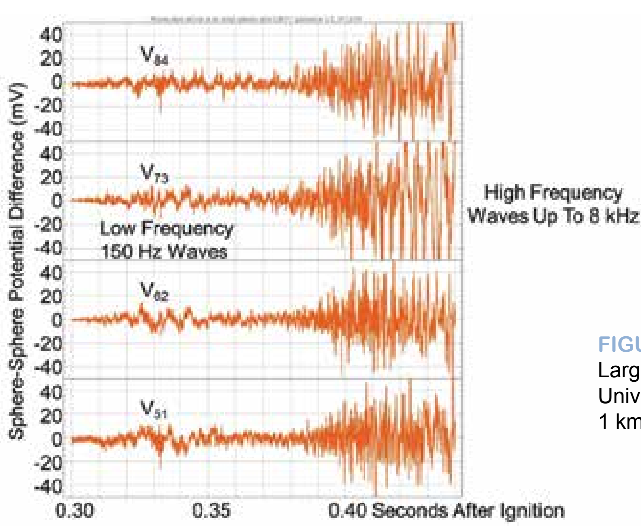

FIGURE 5
Large amplitude plasma waves acquired by the University of Washington electric field sensors 1 km from the CARE II CRV7 injection point.

probes in double-double configurations where there are multiple baselines for measuring electric fields between sensor pairs. Both low-frequency MHD waves and higher frequency ion waves have been identified in the data.

The plasma densities at the CARE II instrument payload were measured with electron saturation current fixed-bias Langmuir probes (FLP), a sweeping Langmuir probe (SLP), and an impedance (or resonance) probe. These probes yielded the background plasma before the CARE II release and the density reductions and plasma irregularities excited by the dust and molecule debris injection. The plasma density instruments used electron saturation currents or the frequency spectrum of the plasma probe impedance to measure the electron densities. The sensitivity of the plasma probes were chosen for electron density ranges between 2.0×10^2 and 1.6×10^6 cm^{-3}. The range for the ions is 2.4×10^4 to 9.4×10^6 cm^{-3}. The electron temperature is also measured between 0.02 and 1.0 eV. The plasma resonance probe covers the 1.2×10^4 to 1.2×10^6 cm^{-3} density range with increased accuracy. The sample rate on the Langmuir probes was 43 kHz for electrons and 10 Hz for electron temperature. The resonance probe was swept with a 10 Hz rate. Samples of the data acquired with the floating and swept Langmuir probes (FLP-A and SLP) are shown in Fig. 6.

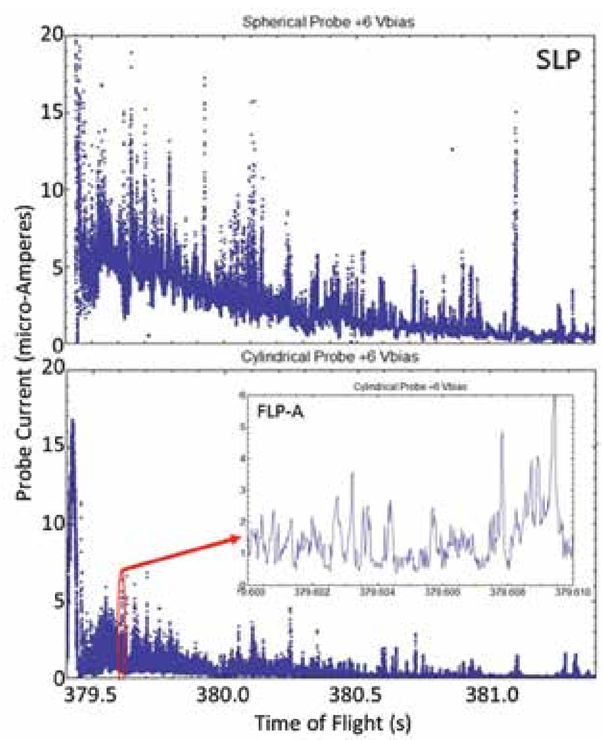

FIGURE 6
The first 2 seconds of the CARE II dust release at a time 370 seconds after launch showing data from NRL Langmuir probes. The sweeping Langmuir probe, (top) and the floating Languire probe-A (FLP-A) (bottom) and an expanded 1/100 of a second of data from FLP-A (inset) cover a period filled with plasma wave activity. The large spikes may be due to charged dust particles striking the probes.

The instrument payload on CARE II was supported by ground radars operating in the high frequency (9 MHz), very high frequency (50 MHz), and ultrahigh frequency (914 MHz) ranges. A preliminary look at the backscatter data showed no effect in the high frequency range, small effect in the very high frequency range, and long lived disturbance in the ultrahigh frequency range. Further analysis is needed to relate the enhanced radar backscatter to the plasma disturbance excited by the CARE II release.

SUPPORTING THEORY FOR CARE II DATA INTERPRETATION

Our two fold goal for ongoing theoretical study of CARE II data is to (1) explain the disturbance observations recorded by the CARE II sensors and (2) predict the magnitude of the plasma turbulence stimulated by the dust injection. The theoretical effort is supported by particle-in-cell and fluid models developed at Virginia Polytechnic Institute and State University and NRL.[2–5] The generation of MHD and Whistler wave modes by localized dust and molecule expansion in the ionosphere uses several wave excitation mechanisms.[1] The MHD model for payload impulse response uses both fluid theory for the MHD shock-wave generation and anisotropic media ray tracing to predict the path of the disturbance wave. Irregularity generation and sensing involves dust and molecule streaming instabilities described by both fluid and kinetic theory. The physics of field aligned irregularities uses both fluid and kinetic descriptions.

ACKNOWLEDGMENTS

The CARE II research program was sponsored by the NRL Base Program. The rocket launch and payload integration were funded by the Department of Defense Space Test Program. The rocket payload was fabricated by the NASA Wallops Flight Facility. Individual ground support was provided by multiple sponsoring agencies in Norway, Germany, Finland, and the United Kingdom.

[Sponsored by the NRL Base Program (CNR funded)]

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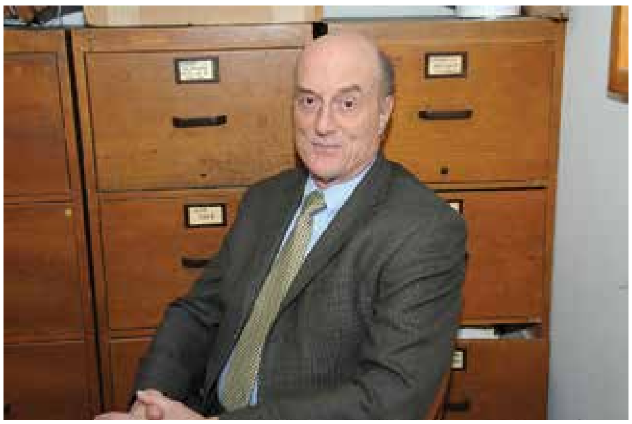

PAUL A. BERNHARDT holds a B.S.E.E. degree and an M.S. degree and a Ph.D. in electrical engineering. He earned his bachelor's degree from the University of California, Santa Barbara, in 1971, his master's degree from Stanford University in 1972, and his doctoral degree from Stanford University in 1976. He is head of the Space Use and Plasma Environment Research Section in the Plasma Physics Division. His primary area of research is remote sensing of the upper atmosphere using radio techniques, including (1) computerized ionospheric tomography (CIT), (2) optical excitation by high-power radio waves, and (3) radar diagnostics of Space Shuttle engine burns. He has been principal investigator on many NASA- and DoD-sponsored experiments. His theoretical interests include modeling of nonlinear interactions of high-power radio waves in the ionosphere, numerical solutions of partial differential equations for fluids and waves, and reconstruction algorithms for tomographic imaging. Dr. Bernhardt has published over 150 papers in refereed journals. Dr. Bernhardt is past chair (1994–1997) for Commission H of the United States National Committee of the International Union of Radio Science, former chair of Subcommission C4/D4 on Active Experiments of COSPAR Experiments (1998–2004), member and previous books-board editor of the American Geophysical Union, and associate editor for *Radio Science*. He is a fellow of the Institute for Electrical and Electronics Engineers and a fellow of the American Physical Society. He is the recipient of the NRL 2011 E.O. Hulburt Award.

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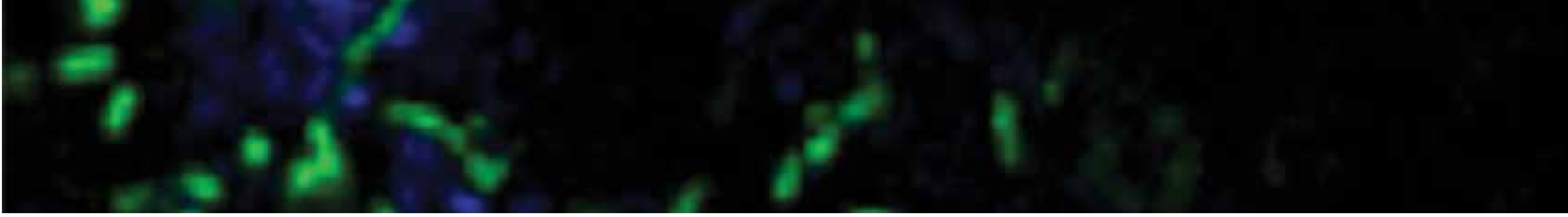
GEORGE GATLING received a B.S. degree in electrical engineering from Brigham Young University in 2002. He started his NRL career designing the control systems for the Space Physics Simulation Chamber. In 2003, he designed and deployed a receiver network in Alaska to search for secondary emissions during HAARP campaigns. He has developed the flight electronics for Langmuir probes and plasma impedance probes used on a variety of platforms from CubeSats to the International Space Station. He is currently completing a Ph.D. in electrical engineering at George Mason University and working in the Space Experiments Section of the Plasma Physics Division, where he is actively involved with research on plasma electrical impedance tomography and plasma impedance measurements.

The MICROBE ELECTRIC and Its POWERFUL IMPACT

The U.S. Naval Research Laboratory (NRL) is known for its leadership in developing the benthic microbial fuel cell (BMFC) as a persistent power supply for marine-deployed applications. The BMFC operates on the bottom of marine environments where it oxidizes organic matter residing in sediment with oxygen in overlying water.

Now investigators in the Center for Bio/Molecular Science and Engineering are envisioning other applications stemming from this research that will go way beyond just generating energy on the sea floor. Our NRL research team is particularly excited about how undersea microorganisms might generate fuel from carbon dioxide, serve as sensors that communicate with autonomous underwater vehicles (AUVs), and even repair AUV onboard circuitry.

Our researchers have made major breakthroughs in recent years. They've learned a lot about the biomolecular pathways that connect bacterial cells to cathode surfaces. They've also identified a novel microorganism with all the right stuff to help them in advancing research that could have a powerful impact on scientific understanding of microbial processes and on crucial military technology and engineering.



Bacteria as Electrochemical Catalysts

S.M. Strycharz-Glaven, B. Lin, Z. Wang, B.L. Eddie, A. Malanoski, D.H. Leary, W.J. Hervey, and L.M. Tender
Center for Bio/Molecular Science and Engineering

Some marine bacteria can form biofilms on electrode surfaces and either produce (microbial bioanodes) or consume (microbial biocathodes) electrical current. Our research team at the U.S. Naval Research Laboratory (NRL) is interested in learning how to harness the physiology of microbial bioanodes to power benthic microbial fuel cells (BMFCs), devices that harvest energy from organic matter on the seafloor. From our basic research on how much power a BMFC can generate, we've learned a lot about the ability of bacteria to transfer electrons over micron-scale distances at the bioanode but not as much about the microbial catalysts and electron transfer reactions at the biocathode. To learn more about the extracellular electron transfer (EET) processes of microorganisms that catalyze reduction reactions at the biocathode, our research team has expanded our microbial electrochemistry research program. Investigations into EET processes will open pathways to the development of such Naval technologies as bioelectrosynthesis of biofuels from CO_2 in seawater and microbial communication with autonomous devices. Building on our discoveries in biocathode EET, we are now taking first steps to integrate the genetic sensors of living bacterial cells with electronic circuitry, as described in detail below. In addition, understanding how to use electrical current to direct the behavior of bacteria could spur the investigation of a wide range of potential Naval applications, e.g., signaling the synthesis of organic polymers to repair components of an autonomous underwater vehicle (AUV) (i.e., synthetic circuit repair). These tiny microbial controllers would mean a crucial leap ahead for the science and engineering of Department of Defense autonomous systems.

BIOCATHODE ELECTRON TRANSFER

In 2015, we made major breakthroughs in understanding the biomolecular pathways that electrically connect bacterial cells to cathode surfaces. We characterized a naturally enriched marine microbial consortium (referred to as Biocathode-MCL) to determine which key organisms were associated with electrode EET and CO_2 fixation, the latter a prerequisite for building the organic carbon compounds that enable bacteria to grow.[1] Understanding how a microorganism fixes CO_2 was key to knowing how to develop electrode-directed synthesis of organic molecules. We approached the problem through metagenomics, metaproteomics, and metatranscriptomics (the study of genetic material, proteins, and gene-expression [RNA-seq], respectively, in environmental samples). From our investigations, we determined that a novel microorganism of the family *Chromatiaceae* had the necessary components for microbial electrosynthesis. For one, the microorganism expressed key proteins believed to be involved in iron oxidation, a physiological process that may be similar to microbial biocathode EET processes. For another, it expressed key proteins involved in CO_2 fixation, suggesting that the microorganism is an electroautotroph (i.e., it can use electrons supplied by the electrode to reduce CO_2 — a goal that is pursued by some researchers through the use of inorganic electrode catalysts). Moreover, we demonstrated modulation of the expression of genes for proteins proposed as components of the Biocathode-MCL EET pathway by changing the electrode potential.[2] This last result suggested that we could manipulate the rate of electrode-linked microbial CO_2 fixation, and thereby actuate microbial electrosynthesis.

ENGINEERED MICROBIAL COMMUNITIES

A major barrier to our work in engineering biosynthetic pathways in the *Chromatiaceae* electroautotroph was our inability to cultivate the microorgansim outside of the cathode biofilm. To find an alternative, we called on the expertise of various researchers interested in studying the microorganism and its activity in situ. In collaboration with PacBio, a DNA sequencing company, we first obtained a fully sequenced genome and then enabled fluorescence in situ hybridization (FISH) analysis to show where this electroautotroph resides within the Biocathode-MCL biofilm. On the basis of sequencing information and FISH analysis, we proposed the candidate genus and species *Candidatus* Tenderia electrophaga (so naming in honor of NRL research biologist Dr. Lenny Tender, a world-renowned pioneer in bioelectrochemical systems research).[3] Because we have been unable to cultivate *Ca*. T. electrophaga, we instead are developing methods to engineer and reintroduce its heterotrophic partner organisms (those that feed on fixed carbon). With these methods, we will use syntrophic interactions (cross-feeding) to convert the organic carbon generated by *Ca*. T. electrophaga into commodity chemicals, such as oleochemicals. We have developed a genetic system for *Marinobacter* sp. strain CP1 known to associate closely with *Ca*. T. electrophaga within Biocathode-MCL. As proof of concept, we produced three initial results: (1) We expressed green fluorescent protein (GFP) in strain CP1. (2) We demonstrated reincorporation of this engineered strain into the biocathode biofilm. (3) We demonstrated the strain's association with *Ca*. T. electrophaga (Fig. 1). Engineering a microbial community exploits the inherent robustness conferred by the community and results in distribution of engineered metabolic burdens.

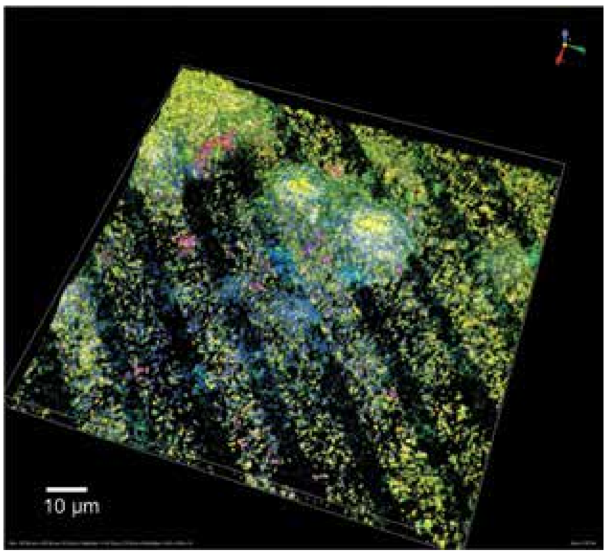


FIGURE 1
Laser scanning confocal microscopy of a Biocathode-MCL biofilm modified with *Marinobacter* sp. strain CP1 (*Marinobacter*-GFP) expressing green fluorescent protein (GFP). *Marinobacter*-GFP incorporates into cell clusters known to contain mostly *Ca*. Tenderia electrophaga.

MULTIDISCIPLINARY MARINE MICROBIOLOGY

We took a multidisciplinary approach to understanding Biocathode-MCL electrode growth. The NRL research community, particularly in the Center for Bio/Molecular Science and Engineering, pooled its spectrum of expertise to help us develop a research program that incorporates microbiology, electrochemistry, Raman microscopy, molecular genetics, metagenomics, metaproteomics, metatranscriptomics, and synthetic biology. To study conductive anodic biofilms of *Geobacter sulfurreducens*, we worked with our microbial electrochemistry group to develop an approach applicable also to studying Biocathode-MCL. To learn whether electrons can travel through the biofilm, we used interdigitated electrode arrays (Fig. 2) and found that Biocathode-MCL, unlike *G. sulfurreducens*, recruits distinct sets of redox mediators, one to carry a charge through the biofilm and another to interact directly with the surface. This phenomenon may stem from the biofilm's mixture of different bacteria, not all capable of surface attachment yet contributing to the conductive nature of the film. We used FISH to determine whether different bacteria were present on the electrode surface or between the interdigitated bands of the electrode and at a distance from the electrode surface. We found that the biocathode biofilm was dominated by clusters of *Cd*. Tenderia electrophaga, with partner bacteria dispersed throughout the clusters. We used confocal Raman microscopy to determine if signatures for proteins associated with the ability of a bacterium to perform EET, such as *c*-type cytochromes, are present in Biocathode-MCL. The Raman profile of Biocathode-MCL was stratified and indicated *c*-type cytochromes near the electrode surface and a unique FeS-type complex accumulating away from the electrode into the biofilm. These results might reflect broader phenomena occurring when marine biofilms form on mineral surfaces in nature.

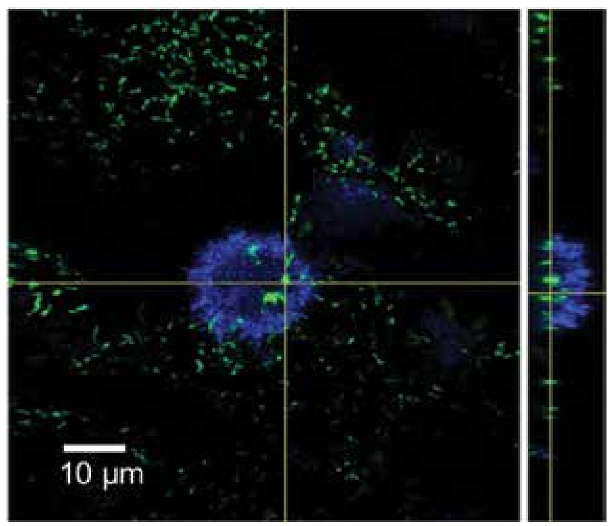


FIGURE 2
Three-dimensional reconstruction of Biocathode-MCL grown on a gold interdigitated microelectrode array with laser scanning confocal microscopy. Bacterial cells are stained with fluorescence in situ hybridization to label different types of bacteria based on their identity. *Ca*. Tenderia electrophaga is labeled light blue to teal in color. Purple cells are *Gammaproteobacteria* and yellow cells are *Alphaproteobacteria*.

IMPACT ON PROTEOMICS AND NAVAL ENGINEERING

Our research is answering fundamental questions about biocathode EET, contributing to the science and spurring the investigation of potential applications for the Navy. In this research, we have studied how bacteria exchange electrons directly with the immediate extracellular environment and how these electrical currents, transmitted over micron-scale distances, communicate with other cells and insoluble substrates. Moreover, this research is driving additional basic science research, much of it garnering wide attention from microbiologists, geo-biologists, and synthetic biologists, among others. Electrode cultivation of microorganisms gives us a stable platform and a real-time monitoring tool for delving into questions we might not otherwise have thought to ask, e.g., how knockout mutagenesis of key proteins for electron transfer pathways might be involved in EET. Furthermore, we are excited about the possibility of comparing our laboratory findings to analogous systems found in such natural environments as deep ocean methane seeps (Fig. 3).

keep the Navy on the forefront of EET-based military technology. To that end, we have launched a new collaborative partnership with the Massachusetts Institute of Technology (MIT), funded through the Office of the Assistant Secretary of Defense for Research and Engineering, to transition *Marinobacter* sp. strain CP1 into a synthetic biology chassis for applications in the marine environment. On the basis of genetic sensor work by Christopher Voigt, professor of microbiology at MIT, we are merging two Office of Naval Research-funded science areas, microbial extracellular electron transfer and synthetic biology, to create mechanisms for controlling autonomous underwater vehicles and for directing the behavior of undersea microorganisms.

Furthermore, we are working in partnership with the U.S. Naval Academy, the Defense Threat Reduction Agency, and the Office of Naval Research on develop-

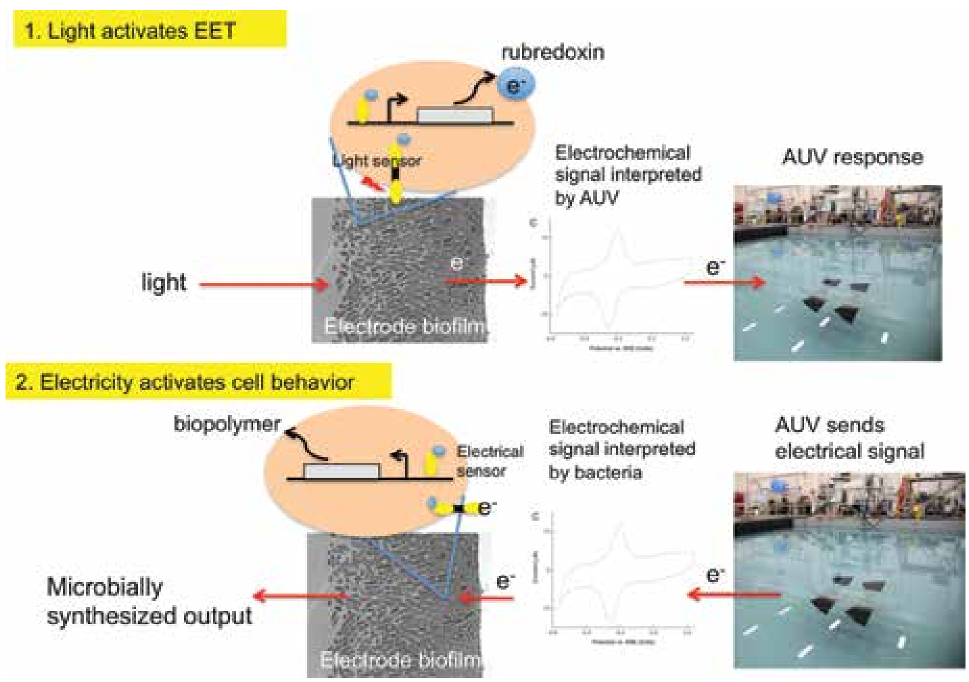


FIGURE 3
Schematic of living microcontrollers for autonomous underwater vehicles (AUVs). In configuration 1, a genetic sensor is used to detect an environmental signal (e.g., light) and activate expression of a redox active molecule that transmits an electrochemical signal to the AUV. The electrochemical signal directs the behavior of the AUV. In configuration 2, an electrochemical potential is sensed by the bacterial biofilm and the applied potential actuates gene expression. Envisioned applications for configuration 2 include synthesis of biopolymers that could be used to repair components of the AUV.

Our work is crucial to addressing Naval technological and engineering needs. This research meets priorities of the Naval Science and Technology Strategic Plans, particularly in the field of autonomy and unmanned systems, including bio-inspired systems for distributed sensors, microrobotic systems, and synthetic biology for integration of biology and machines.

Continued collaboration and partnership is key to assembling the skills and intellect that it will take to

ing training programs for midshipmen about synthetic biology by participation in the International Genetically Engineered Machines (iGEM) competition, with the hope of sustaining in our Naval officer corps long-term and in-depth understanding of this ever-evolving science and increasingly critical technology.

[Sponsored by ONR and the NRL Base Program (CNR funded)]

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THE AUTHORS

SARAH STRYCHARZ-GLAVEN began her science career at the University of Massachusetts, Amherst, where, as an undergraduate, she studied phytoremediation (the direct use of living green plants to remediate environmental contaminants). She earned an M.S. degree in molecular and cellular biology in 2002 from UMass-Amherst and a Ph.D. in environmental health sciences in 2006 from the University of South Carolina. Dr. Glaven returned to UMass-Amherst in 2006 as a postdoctoral researcher with Derek Lovley, Distinguished University Professor in Microbiology. In 2009, Dr. Glaven joined NRL to study microbial electrochemistry under the mentorship of Dr. Lenny Tender. Her work at NRL has contributed to fundamental understanding of electron transfer in microbial biofilms on electrodes. Her current research focuses on engineering, through synthetic biology, the interaction between bacteria and electrodes to improve energy from microbial fuel cells, enhance biocatalysis during electrosynthesis, and direct cellular behavior.

BAOCHUAN LIN is the deputy laboratory head of the Laboratory for Biomaterials and Systems in the Center for Bio/Molecular Science and Engineering. She graduated from George Washington University after completing her dissertation research at the National Institute of Child Health and Human Development. She also studied satellite DNA replication of tomato leaf curl virus in 2000 in Australia. In 2001, she joined NRL, where she became a federal employee in 2004. She has been involved in a number of projects to identify gene expression profiles of various cells in response to different stimuli. She also developed a microarray-based detection system for differentiating common respiratory pathogens and biothreat pathogens. For her contributions in the area of resequencing pathogen microarrays, she is the recipient of the 2006 Navy Top Scientists and Engineers Award, the 2009 Federal Laboratory Consortium Award for Excellence in Technology Transfer, and the 2011 Sigma Xi Applied Science Award, Naval Research Laboratory Edison Chapter. Her research focuses on using system and synthetic biological approaches to study microbial consortium for bioenergy production. She also is interested in studying the epigenetic mechanisms underlying the pathogenesis of exposure to chemical and biological threats.

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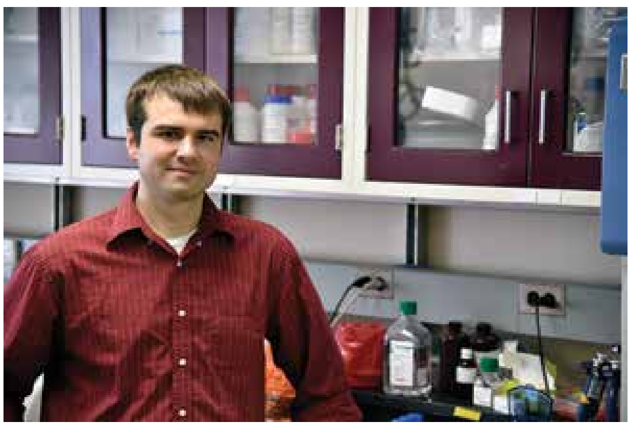
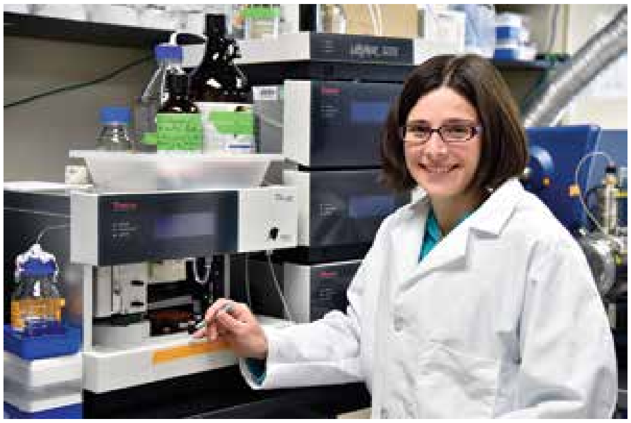
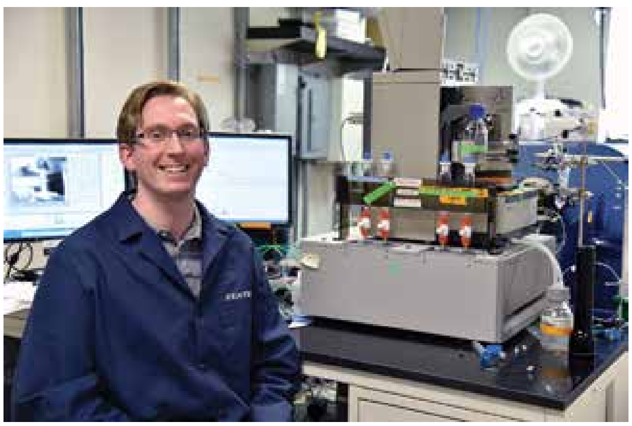


BRIAN J. EDDIE holds a B.S. and an M.S. degree, both in microbiology, from Arizona State University. In 2013, after earning a Ph.D. in marine studies from the University of Delaware, he joined NRL as an American Society for Engineering Education postdoctoral fellow. In 2016, he was hired as an NRL research biologist in the Laboratory for Biosensors and Biomaterials in the Center for Bio/Molecular Science and Engineering, where he focuses on the bioimaging and systems biology of bacteria. His research interests include understanding the structure and function of microbial biofilms and manipulating them to provide enhanced or novel functions.

ANTHONY P. MALANOSKI earned a doctoral degree in chemical engineering in 1999 from the University of Massachusetts, Amherst. His research at UMass-Amherst incorporated Monte Carlo simulations in the study of the thermodynamics of the solid-fluid phase equilibrate of short-chain molecules. Dr. Malanoski conducted postdoctoral work at the University of New Mexico and Sandia National Labs in oil-water-surfactant phase equilibria and pore condensation (using Monte Carlo, molecular dynamics, and density functional theories). In 2002, he joined the Center for Bio/Molecular Science and Engineering at NRL, where he applied his interest in thermodynamics to new areas of investigation, including response of liquid crystals to sound and binding of oligonucleotides to microarray surfaces. His current projects focus on modeling key processes in a range of systems, including reaction kinetics on organic-nanoparticle hybrids; adsorption phenomena in ordered porous materials; binding to porphyrin functionalized materials for sensing; and bioinformatics processing, including WGS assembly of metagenomic samples, 16S abundance calculations, and differential expression analysis. Dr. Malanoski is recipient of the 2009 Federal Laboratory Consortium Award for Excellence in Technology Transfer and several publication and patent awards. Author of 63 publications with more than 1,400 citations, he has an h-index of 21.



DAGMAR H. LEARY earned an M.S. degree in biotechnology and applied biology from the Institute of Chemical Technology in Prague, Czech Republic, and a Ph.D. in pharmacology from Case Western Reserve University. Her dissertation focused on circadian proteome changes in photoreceptor outer segments. She joined NRL as a National Research Council postdoctoral research associate in 2010, and she was later hired as an NRL research biologist. Her NRL research focuses on developing metabolomics and proteomics methods for analyzing samples from marine environments.



JUDSON HERVEY holds a B.S. degree in biology from West Liberty University and a Ph.D. from the Graduate School of Genome Science at the University of Tennessee-Oak Ridge. He joined NRL as a postdoctoral fellow in 2009. He was hired in 2012 as an NRL research biologist in the Laboratory for Biosensors and Biomaterials in the Center for Bio/Molecular Science and Engineering, where he has applied expertise in mass spectrometry (MS) to several multidisciplinary research programs. He leads a program leveraging high performance computing (HPC) of large scale biomolecular "-omics" datasets in systems and synthetic biology. His primary research interests include microbiology, MS-based proteomics, deployment of bioinformatics applications to HPC, and analytical biochemistry.

LEONARD M. TENDER is a research chemist and head of the Laboratory of Molecular Interfaces in the Center for Bio/Molecular Science and Engineering. He earned a B.S. degree in chemistry from Massachusetts Institute of Technology and a Ph.D. in analytical chemistry from the University of North Carolina. He was a postdoctoral fellow at the University of California, Berkeley, before joining NRL in 1997.

Chasing atmospheric waves to the edge of space

What happens when you combine strong winds and a mountain range? You've probably experienced what happens if your airline flight has ever been bumpy. If you've operated a glider, you've gotten an incredible lift from the upward movement of air. But mountain waves, also more generally called gravity waves, can create the kind of turbulence that spells big trouble for any aircraft, enough trouble, in fact, to shear the engine off of a DC-8 airplane, to cite one well-known example.

Our U.S. Naval Research Laboratory scientists have led the way in gravity wave research, on the ground with models and theory, and in research aircraft in the skies over mountains and the open oceans. Recently, they flew over New Zealand and the nearby Tasman Sea and Southern Ocean, as part of an atmospheric observation campaign called the Deep Propagating Gravity Wave Experiment (DEEPWAVE). The campaign was the first project to measure gravity waves propagating all the way up to the edge of space at 100 kilometers above Earth's surface.

The better knowledge of gravity waves resulting from DEEPWAVE should help improve turbulence forecasts for aviation, weather forecast skill generally, and other operations, according to the research team—something you might think about the next time your airplane's seatbelt sign goes ***bing***!

Mysteries of the Deep: Flying through New Zealand's Gravity Waves

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The recent Deep Propagating Gravity Wave Experiment (DEEPWAVE) represented a significant advance over previous field experiments in several respects. Most important, it was the first project to follow gravity waves from near the surface to the lower thermosphere. The U.S. Naval Research Laboratory (NRL) was one of the lead organizations of DEEPWAVE. A Gulfstream-V research aircraft used multiple technologies to take high-resolution and high-precision measurements of the atmosphere from the surface up to altitudes of approximately 100 km. The technologies included dropwindsondes (small expendable measuring devices equipped with parachutes and dropped from aircraft) and new remote-sensing instruments, such as lidars and airglow imagers that measure key atmospheric parameters up to an altitude of around 100 km. Another aircraft, a Falcon 20, flew at lower altitudes in coordination with the Gulfstream-V and took measurements up to an altitude of 11 km. Findings from more than two dozen research flights, from June through July of 2014, over New Zealand, the Tasman Sea, and the Southern Ocean, are increasing our understanding of gravity waves, particularly their propagation to high altitudes. The findings also have important implications for future U.S. Navy needs and capabilities, including improved weather and climate predictions.

ATMOSPHERIC GRAVITY WAVES

Gravity waves occur naturally in any stratified fluid because the balancing forces of gravity and buoyancy support simple harmonic motion. Gravity waves occur in the deep ocean as internal waves and on the ocean surface as ocean waves. Since density decreases with altitude, the atmosphere, like the ocean, is suffused with gravity waves. Surface winds flowing across mountains generate three-dimensional orographic gravity waves, also known as mountain waves, in much the same way that ships and submarines generate gravity waves and internal waves, respectively, in their wakes. Intense storms and imbalances from jet streams also generate atmospheric gravity waves. The nature of gravity waves, particularly those that propagate from the lower atmosphere to much higher levels, has remained a mystery for many decades. Only through DEEPWAVE, an initiative co-led by NRL, have researchers attained a more complete understanding of deep propagating gravity waves and their impacts on the atmosphere.

Gravity waves are significant contributors to atmospheric circulation and Earth's climate. Mountain waves influence distributions of several types of clouds, including high-altitude cirrus clouds, which play important roles in weather and climate, and polar stratospheric clouds, which are sites for the chemical reactions responsible for producing an ozone hole over Antarctica. Just as ocean gravity waves break on the shore or produce large waves during maritime storms that endanger ships, breaking atmospheric gravity waves pose a severe turbulence hazard for aviation. For example, the Navy's MQ-4C Triton aircraft, used for Broad Area Maritime Surveillance, operates in the stratosphere at altitudes where conventional weather-related sources of turbulence are absent but where breaking gravity waves are present as the major cause of severe clear-air turbulence.

The continuous breaking of gravity waves transports and deposits enough momentum and energy to impact the meteorology and climate of the entire planet at all scales. Models used for climate and weather prediction cannot adequately resolve the processes and dynamics associated with this wave activity, because gravity waves exist at horizontal scales from about 1 to 1000 km whereas current computer models operate at horizontal resolutions in the 10 to 100 km range (which effectively only resolve waves in the 100 to 1000 km range). To improve forecasting of these critical gravity-wave impacts on the atmospheric circulation, scientists must parameterize these processes with a sub-grid scale model within weather and climate models. A better understanding of gravity-wave dynamics will lead to advances in the parameterization of the models and improvements in the skill of model forecasts.

Unlike the ocean, Earth's atmosphere has no natural upper boundary, a feature that allows gravity waves to propagate to high altitudes where the waves attain large amplitudes and exert even greater effects. Gravity-wave drag drives the meteorology and climate of the entire stratosphere and mesosphere (altitudes of 10 to 100 km) in much the same way that clouds and convection drive the major aspects of weather and climate nearer to the surface. Gravity waves also propagate into the upper atmosphere (altitudes of 80 to 300 km), where they distort the ionized plasma. This atmospheric disturbance can affect a range of U.S. Navy-relevant communication, surveillance, and geolocation technologies that involve electromagnetic signal propagation through the ionosphere.

DEEPWAVE

Gravity waves have been studied intensively over the past few decades. Recent research has highlighted the need for better understanding of gravity-wave influences through deep layers of the atmosphere. The idea for an aircraft mission emerged in 2008 from discussions among NRL researchers James Doyle, of the Marine Meteorology Division, Steve Eckermann, of the Space Science Division, Ron Smith, Damon Wells Professor of Geology and Geophysics at Yale University, and Dave Fritts, atmospheric dynamics researcher and founder of the Colorado division of GATS, Inc., an aerospace firm specializing in instrument development and systems for atmospheric remote-sensing missions. They proposed using the National Science Foundation/National Center for Atmospheric Research (NSF/NCAR) Gulfstream-V research aircraft (Fig. 1(g)) to observe gravity waves in the Southern Hemisphere, near either the Southern Andes of Argentina and Chile or the Southern Alps of New Zealand.

DEEPWAVE coalesced multidisciplinary expertise and broad-based support from many different areas

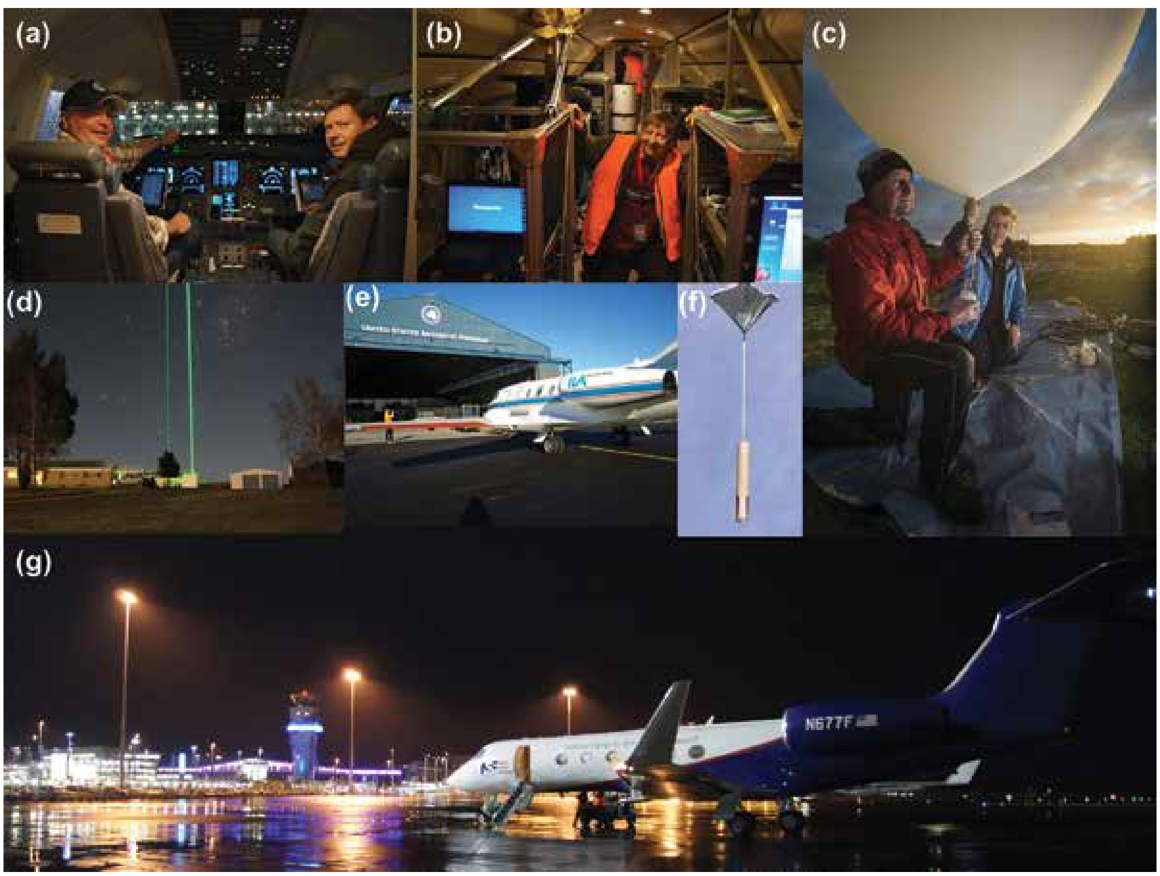

FIGURE 1
Photos from the DEEPWAVE field deployment in New Zealand: (a) National Center for Atmospheric Research (NCAR) pilots on the Gulfstream-V; (b) Mike Taylor, of Utah State University, amid the instrument racks aboard the Gulfstream-V. The white telescope assembly for the Gulfstream-V lidars, which profiled the atmosphere up to approximately 100 km altitude, is visible immediately behind Dr. Taylor; (c) Tony Bromley and Sally Gray, of New Zealand's National Institute of Water and Atmospheric Research (NIWA), prepare to release a weather balloon in Haast, New Zealand [image credit: Dave Allen, NIWA]; (d) German Aerospace Center lidar systems at Lauder, New Zealand, measure atmospheric temperature profiles up to an altitude of approximately100 km; (e) the German Aerospace Center Falcon aircraft entering the U.S. Antarctic Program hangar at Christchurch Airport; (f) NCAR dropwindsonde in flight; (g) the NCAR Gulfstream-V on the tarmac at Christchurch Airport just prior to another DEEPWAVE research flight.

of atmospheric science (e.g., lower, middle, and upper atmosphere, and weather and climate). The widespread interest prompted NSF to fast-track development of three new remote-sensing instruments that would equip the Gulfstream-V to observe the atmosphere at much higher altitudes than previously possible. The instruments were (a) a Rayleigh lidar to measure densities and temperatures at altitudes from approximately 30 to 60 km, (b) a resonance lidar to measure atmospheric sodium densities and temperatures at altitudes from approximately 75 to 100 km (Figs. 1(b) and 1(c)), and (c) an Advanced Mesospheric Temperature Mapper (AMTM) to measure atmospheric airglow emissions and temperatures in a horizontal plane at approximately 87 km in altitude, with a field of view of approximately 120 × 80 km^2. The resulting altitude coverage of all atmospheric measurements from the Gulfstream-V is shown on the top left panel of Fig. 2.

Both the Southern Andes and the Southern Alps produce planetary maxima, or "hot spots," in gravity-wave activity during austral winter, when a stable weather pattern of westerly winds extending to high altitudes, known as the polar vortex, allows for deep propagating gravity waves. Due to mild winter weather and excellent infrastructure, the research team decided to base DEEPWAVE close to the Southern Alps on the South Island of New Zealand at the Christchurch International Airport.

Intensive modeling and satellite data analysis indicated that this region exhibited "hot spots" in deep orographic gravity-wave activity over both New Zealand and Tasmania as well as sources of nonorographic grav-

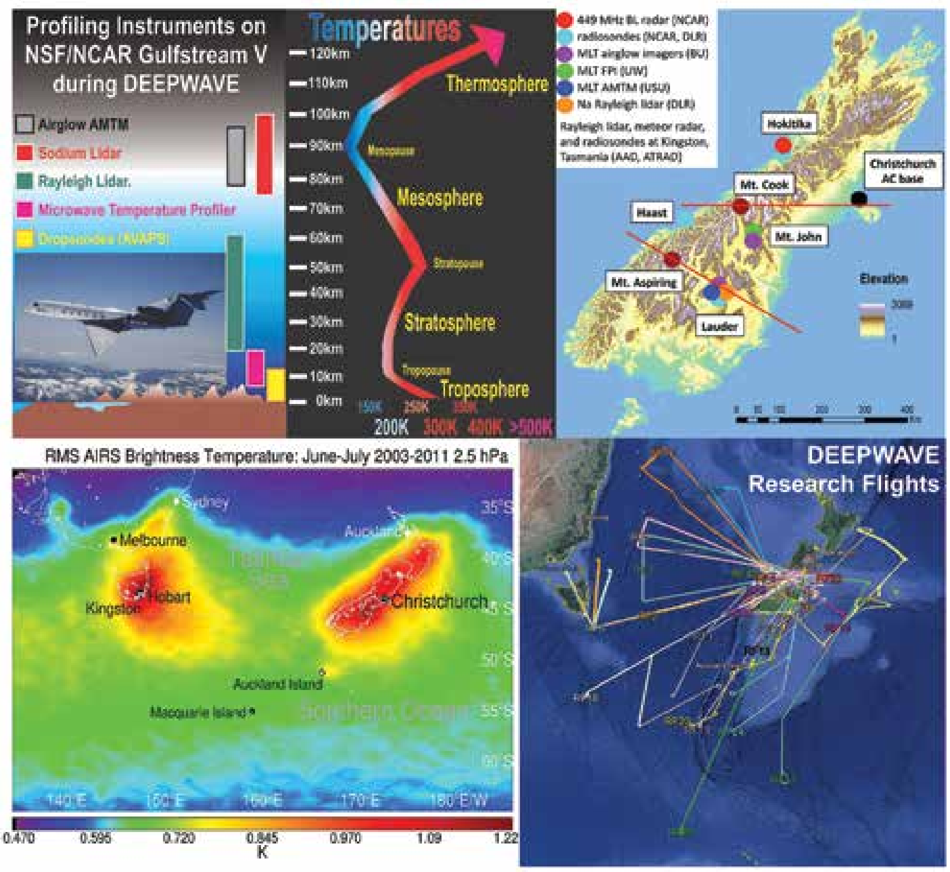

FIGURE 2

Top left: Measurement altitudes of Gulfstream-V instruments acquiring vertical atmospheric profiles above and below the aircraft during DEEPWAVE. The Gulfstream-V flew at an altitude of about 12 km. Top right: Ground-based instruments contributing data to DEEPWAVE in New Zealand and elsewhere (see legend). The major orographic features are Mt. Cook and Mt. Aspiring. Red lines show typical Gulfstream-V and Falcon flight tracks. Bottom left: Gravity wave variance at an altitude of about 40 km derived from Atmospheric Infrared Sounder (AIRS) measurements from the Aqua satellite over the DEEPWAVE region. Bottom right: Ground tracks of all 26 Gulfstream-V research flights (Research Flights 1–26) conducted during DEEPWAVE. Acronyms: NSF/NCAR = National Science Foundation/National Center for Atmospheric Research; AMTM = Advanced Mesospheric Temperature Mapper; DLR = German Aerospace Center; BU = Boston University; UW = University of Washington; USU = Utah State University; MLT = mesosphere and lower thermosphere; FPI = Fabry-Perot Interferometer.

ity waves from storm systems in the Southern Ocean (Fig. 2, bottom left panel). Plans for an intensive six-week Gulfstream-V measurement campaign targeted June and July of 2014, when available observations and modeling indicated the strongest deep wave activity in this region.

In 2013 and early 2014, the new Gulfstream-V instruments were flight tested, and DEEPWAVE forecasting tools and flight strategies were tested and refined. The DEEPWAVE field measurement phase took place from May through July of 2014 and involved a team of more than 100 participating scientists.[1] Gulfstream-V flights were planned and supported by a large temporary operations center at Christchurch International Airport. Forecasting and flight planning were supported by a suite of global, mesoscale, and regional models that included the Navy's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®) and Navy Global Environmental Model (NAVGEM). NRL scientists played central roles throughout the six-week field deployment in forecasting weather and planning and executing scientific research flights for the Gulfstream-V (Fig. 1).

The new optical AMTM and lidar instrumentation on the Gulfstream-V required performing almost all research flights at night. Thus DEEPWAVE operated on a nearly continuous around-the-clock schedule — forecasting, flight planning, and research flight debriefs during the day and research flights at night. In all, the Gulfstream-V made 26 DEEPWAVE research flights around the greater New Zealand region (Fig. 2, bottom right panel), completing 180 flight hours and releasing 279 dropwindsondes (Fig. 1(f)).

The success of DEEPWAVE was attributable, in good part, to the many national and international partners who worked in collaboration with the NRL research team. NSF supported a temporary deployment of an extensive ground-based measurement network in New Zealand to support DEEPWAVE with high-resolution high-altitude radiosondes launched from several sites on the South Island and a 449 MHz radar from NCAR that continuously profiled winds from about 0.5 to 5 km altitude on the west coast of the South Island. The German Aerospace Center contributed additional ground-based measurements in New Zealand from radiosondes and lidars (Fig. 1(d)) as well as their Falcon research aircraft (Fig. 1(e)), along with a large team of in-field scientists, support staff, and student researchers. U.S. scientists also deployed and operated a number of mesospheric remote sensors on the South Island during DEEPWAVE. New Zealand's National Institute of Water and Atmospheric Research (NIWA) and Meteorological Service offered local forecasting and field resources with dedicated personnel provided on site. The Australian Bureau of Meteorology provided on-demand radiosonde launches from their sites in Tasmania and Macquarie Island. The University of Adelaide deployed a meteor radar in Tasmania to continuously measure winds from around 80 to 100 km throughout the experiment. This observing network is summarized in the top right panel of Fig. 2.

HIGHLIGHTS OF NRL DEEPWAVE RESULTS

DEEPWAVE research components led by NRL included (1) a comprehensive study of the predictability of deep propagating gravity waves that highlights the surprisingly large impact of targeted dropwindsondes on high-resolution forecasts, (2) the discovery of large-amplitude, breaking gravity waves at high altitudes when diagnosed surface forcing is weak, (3) the most complete documentation ever of large-amplitude gravity waves at high altitudes emanating from small sub-Antarctic islands, and (4) advanced versions of the Navy's COAMPS and NAVGEM developed for DEEPWAVE research by NRL with new high-altitude capabilities.

DEEPWAVE was unique as the first-ever project to assess the predictability of deep-propagating gravity waves, an effort led by NRL investigators James Doyle, Carolyn Reynolds, and Patrick Reinecke, all from the Marine Meteorology Division. Figure 3 shows an example of NRL predictability diagnostics used for the Gulfstream-V sampling strategies. The Navy's COAMPS forecast and adjoint models[2] were used to compute the forecast sensitivity to the initial state, and these regions of high sensitivity were targeted for additional dropwindsonde observations deployed from the Gulfstream-V. The color shading in the Tasman Sea (Fig. 3(a)) highlights the regions where the 24-hour forecast of COAMPS within the gray box is most sensitive to the initial-state 700-hPa east-west winds. These sensitive regions most strongly influenced gravity wave launching and amplitudes over the South Island 24 hours later. Green dots along the flight track show the locations of dropwindsondes deployed from the Gulfstream-V for this assessment. The evolved perturbations (24 hours) based on the sensitivity (Fig. 3(b)) show a maximum over the South Island. These perturbations grow by an order of magnitude over 24 hours, highlighting the potential limits of predictability due to forecast uncertainties in the low-level winds. The key discovery of large forecast improvements due to the dropwindsondes deployed in these sensitive regions underscores the potential for targeted observations to improve mesoscale predictions for not only gravity waves but also broader Navy applications sensitive to the environment. Several research projects are ongoing related to this important work.

The DEEPWAVE field measurements led to the surprising discovery of large-amplitude, breaking gravity waves at high altitudes when diagnosed surface forcing

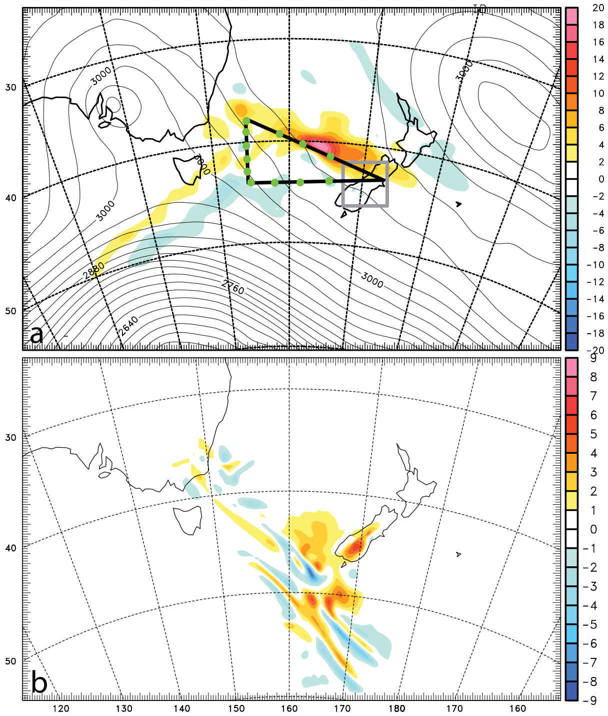

FIGURE 3

(a) Sensitivity of 24-hour Coupled Ocean/Atmosphere Mesoscale Prediction System forecast of kinetic energy in the lowest 1 km above the surface (gray box) to the initial-state 700-hPa east-west wind at 0600 Coordinated Universal Time (UTC) on June 13, 2014 (color scale with interval of 2×10^{-3} m s^{-1}). (b) The evolved perturbations (m s^{-1}) based on the scaled sensitivity after 24 hours of integration at 800 hPa near the crest-level height for the east-west wind, valid at 0600 UTC on June 14, 2014. The Gulfstream-V flight track and locations of dropwindsondes (green dots) are shown in (a). The 700-hPa geopotential height analysis is shown in (a) at a contour interval of 30 m. The sensitivities in (a) are scaled by 105 km^{-3}.

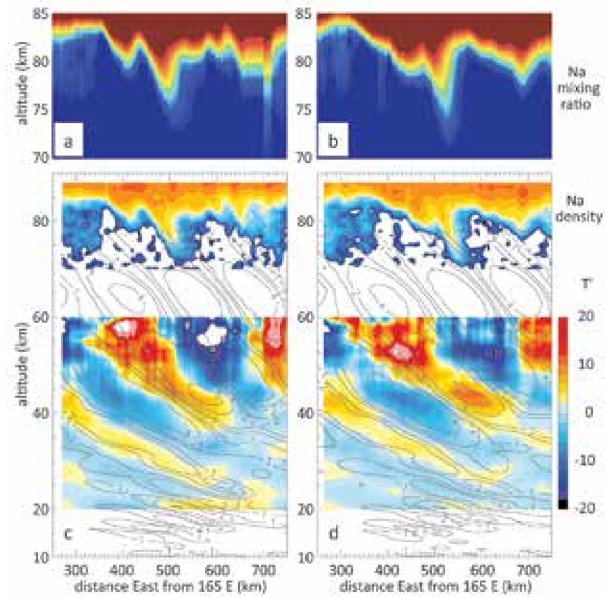

FIGURE 4

Colors show Gulfstream-V observations of (top) sodium lidar mixing ratios, (middle) sodium lidar densities, and (bottom) Rayleigh lidar temperature perturbations during Research Flight 22 as the aircraft traversed back and forth over Mt. Cook (see red flight tracks in Fig. 2). These observations reveal large-amplitude, large-scale waves at all altitudes with intense wave breaking signatures at approximately 80 km. Black lines show corresponding temperature perturbations derived from operational analyses of the European Centre for Medium-Range Weather Forecasts.

was concurrently weak (in spite of having been strong earlier). Observations from Research Flight 22 on July 13, 2014, devised and led by NRL researcher Steve Eckermann, revealed spectacular large-amplitude large-scale gravity waves at all altitudes (Fig. 4).

We investigated how the forecast models performed in predicting this and other large-scale wave events observed up to quite high altitudes. Black contours in Fig. 4 show temperature perturbations from the operational analysis of the European Centre for Medium-Range Weather Forecasts (ECMWF), revealing a wave of tilted phase structure similar to that observed by the Gulfstream-V lidar but with much smaller amplitude than observed. The dynamics of these events are the subject of ongoing research at NRL and in the DEEPWAVE community.

The ECMWF prediction model operates at much higher resolution than NAVGEM, a consequence of the European Centre's greater computational resources. Nevertheless, a research version of NAVGEM applied in the post-mission research phase exhibited skill in capturing gravity waves comparable to those of the ECMWF model. Figure 5 shows an example from Research Flight 25 where temperatures measured by the Microwave Temperature Profiler (MTP) and Rayleigh lidar (Fig. 5, top row) along the Gulfstream-V flight track are compared to results from a high-altitude NAVGEM reanalysis experiment (Fig. 5, middle row) and the ECMWF operational analysis (Fig. 5, bottom row). The Gulfstream-V observations reveal signatures of large-scale gravity waves generated at lower altitudes by storm systems and unstable jet streams over the Southern Ocean. Similar wave structures are accurately captured in both the NAVGEM and ECMWF analyses, although the coarser vertical and horizontal resolution of NAVGEM limits the fine-scale wave structure it can resolve. The research NAVGEM simulations extend to higher altitudes than ECMWF and preliminary comparisons to Gulfstream-V measurements from 75 to 90 km altitude reveal surprisingly close agreement.

Another spectacular NRL-led DEEPWAVE discovery occurred during Research Flight 23, when unexpectedly large-amplitude gravity waves were observed from the Gulfstream-V at high altitudes, emanating from the tiny sub-Antarctic Auckland Island archipelago (Fig. 6(a)). The discovery of intense deep wave activ-

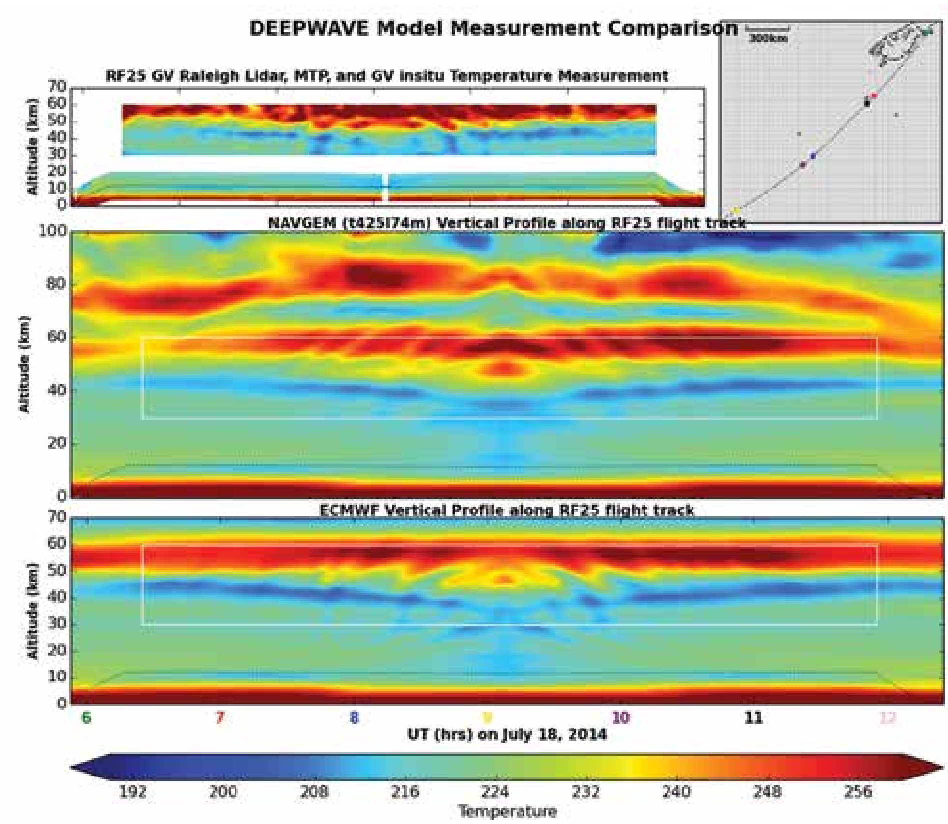

FIGURE 5

Temperature cross sections as a function of height and time along the flight track of DEEPWAVE Research Flight 25 (shown top right). The plots show (top left) Gulfstream-V measurements from the Rayleigh lidar (30 to 60 km) and Microwave Temperature Profiler (MTP), (middle) reanalysis from the Navy Global Environmental Model (NAVGEM), and (bottom) operational analysis from the European Centre for Medium-Range Weather Forecasts (ECMWF). White box shows lidar data area. Blue dashed lines show flight altitude of the Gulfstream-V. Note the large-scale gravity wave banding in the observations and analyses.

ity over a tiny island far from major mainland terrain has turbulence-hazard implications for autonomous assets, such as those used for Broad Area Maritime Surveillance, which operates at high altitudes in remote maritime environments. It can also help NRL researchers improve the representation of unresolved gravity waves in Navy weather prediction models.

Initial modeling of this island-forced gravity wave event demonstrates the promise of tools under development at NRL, which, when combined in innovative ways, will help the U. S. Navy accurately predict deep gravity-wave effects that impact Naval high-altitude aircraft and radar-based systems affected by the ionospheric environment. The Gulfstream-V flight pattern, devised and led by NRL researcher James Doyle (as the Research Flight 23 mission scientist), involved a complex series of stair-step transects of the island parallel to the forecast upstream flow at different flight altitudes (Fig. 6(b)). Lidar data revealed a spectacular large-amplitude breaking gravity wave at ~78 km altitude (Fig. 6(c)). Likewise, the AMTM imaged large-amplitude wave banding in airglow emissions downstream of the island at a similar altitude (Fig. 6(d)). NRL has subsequently led scientific analysis of the dynamics that produced this unexpected gravity-wave event.[3] An NRL Fourier-ray simulation of this event used NAVGEM reanalysis and dropwindsonde data to constrain the upstream environment of the simulation (Fig. 6(e)). After accounting for airglow observing effects, the simulation (Fig. 6(e)) and observations (Fig. 6(d)) show remarkable similarities. This research is ongoing.

SUMMARY

Many mysteries remain about gravity waves — their sources, their dynamics, and their impact on the atmosphere. However, DEEPWAVE has unearthed a wealth of new data that is revolutionizing our understanding of deep gravity-wave dynamics. The DEEPWAVE dataset will provide a valuable resource for the study of gravity waves in Earth's atmosphere for many years to come, and it will continue to give NRL scientists and others new insights into gravity waves and their coupling between lower and higher altitudes in the

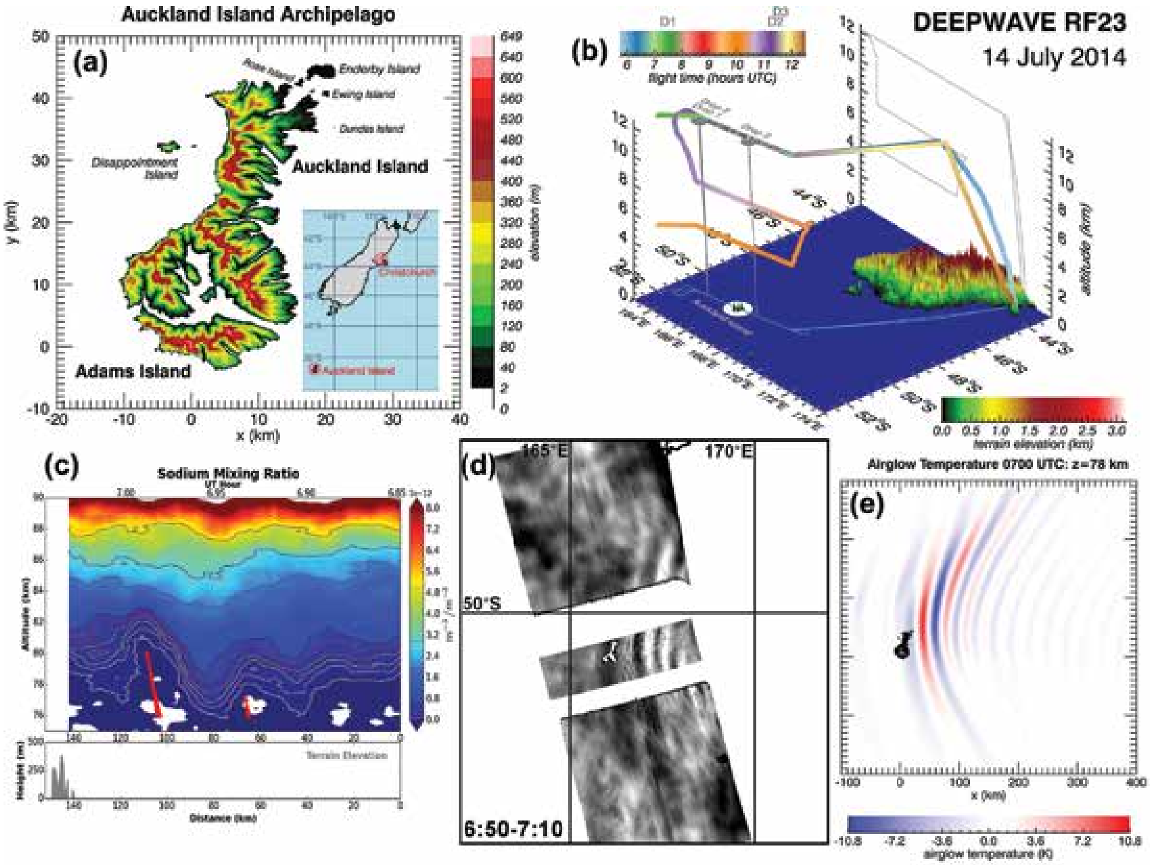

FIGURE 6

(a) Terrain elevations of the Auckland Island archipelago, with location (inset panel) shown relative to Christchurch. (b) Flight path of Gulfstream-V Research Flight 23 from Christchurch to repeated transects over the Auckland Islands on July 14, 2014. Dropwindsonde releases are marked in gray, time by color along flight path. Auckland Islands are spotlighted in white. (c) Sodium densities measured by the Gulfstream-V lidar over the Auckland Islands showing a large-amplitude breaking gravity wave at approximately 78 km altitude near the island terrain (lower panel). (d) Gulfstream-V Advanced Mesospheric Temperature Mapper (AMTM) airglow imagery showing banded wave structure near the Auckland Islands. (e) NRL Fourier-ray simulation using Navy Global Environmental Model (NAVGEM) reanalysis winds and temperatures, then converted to airglow responses, showing strong similarities to AMTM observations.

atmosphere. With advances in instrumentation and improved understanding of gravity waves, we are positioned to develop more physically realistic models that ultimately will improve the Navy's ability to predict and navigate weather and climate.

ACKNOWLEDGMENTS

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[Sponsored by the NRL Base Program (CNR funded)]

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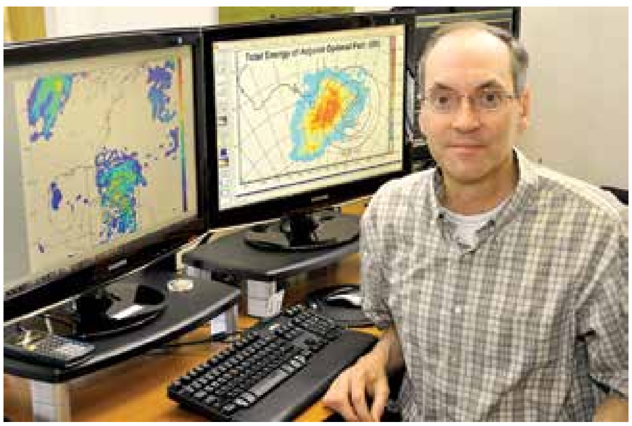
THE AUTHORS

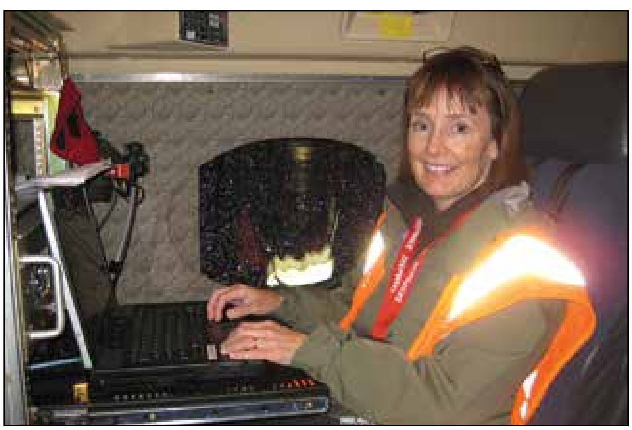


JAMES D. DOYLE earned a B.S. degree in atmospheric science and mathematics from the University of Wisconsin-Milwaukee in 1983 and a Ph.D. in meteorology from the Pennsylvania State University in 1991. He joined the Marine Meteorology Division in Monterey, California, in 1992, where he has served as head of the Mesoscale Modeling Section in the Atmospheric Dynamics and Prediction Branch since 1997. He is one of the lead developers of the U.S. Navy's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) and COAMPS-Tropical Cyclone (COAMPS-TC), which are used to support operational U.S. Navy and U.S. Department of Defense interests globally as well as basic research at NRL and many other universities and laboratories. Currently, he leads efforts for improving the physical understanding and prediction of mesoscale phenomena, such as tropical cyclones, air-sea interaction, and topographically forced flows and gravity waves. He also collaborates frequently with NRL's Oceanography and Space Science Divisions. He is a recipient of the Top Navy Scientists and Engineers of the Year Award, the 2014 Dr. Arthur E. Bisson Prize for Naval Technology Achievement (from the Office of Naval Research), and the 2015 NASA Group Achievement Award for the Hurricane and Severe Storm Sentinel project. He is a fellow of the American Meteorological Society. He was one of the lead co-principal investigators of DEEPWAVE.

STEVE ECKERMANN is a physicist in the Geospace Science and Technology Branch of the Space Science Division, where has worked since 1998. His current research focuses on upper altitude regions of the U.S. Navy's operational global weather prediction systems, primarily the Navy Global Environmental Model, research performed in close collaboration with teams of scientists in NRL's Marine Meteorology, Space Science, and Remote Sensing Divisions. His formal recognitions include the 2013 NRL Sigma Xi Award for Applied Science, the 2013 American Meteorological Society Editor's Award of the *Journal of the Atmospheric Sciences,* and the 2008 Navy Meritorious Civilian Service Award. He was one of the lead co-principal investigators of DEEPWAVE.

QINGFANG JIANG received a Ph.D. in meteorology from Yale University in 2001. He worked in the Marine Meteorology Division as a University Corporation for Atmospheric Research visiting scientist between 2002 and 2012 before becoming a staff physical scientist in 2012. His research interests include stratified flows, gravity wave dynamics, mesoscale modeling and dynamics, air-sea interaction, and large eddy simulation of marine boundary layer. A DEEPWAVE team member, he is investigating trailing waves over New Zealand and non-orographic waves over the Southern Ocean using field observations from DEEEPWAVE, the U.S. Navy COAMPS model, and theoretical tools.

PATRICK A. REINECKE is a research meteorologist in the Marine Meteorology Division's Atmospheric Dynamics and Prediction Branch in Monterey, California. His research focuses on the development and enhancement of numerical weather prediction (NWP) systems, with the goal of providing improved probabilistic and deterministic prediction for day-to-day and high-impact weather. Dr. Reinecke is a primary developer of the U.S. Navy's next-generation NWP system targeted for the exascale computing environment. When completed, this system will be capable of producing high-resolution global weather guidance ranging from days to months. Dr. Reinecke is the recipient of several major awards, including the 2014 Dr. Arthur E. Bisson Prize for Naval Technology Achievement (from the Office of Naval Research) and the 2015 NASA Group Achievement Award for the Hurricane and Severe Storm Sentinel project.

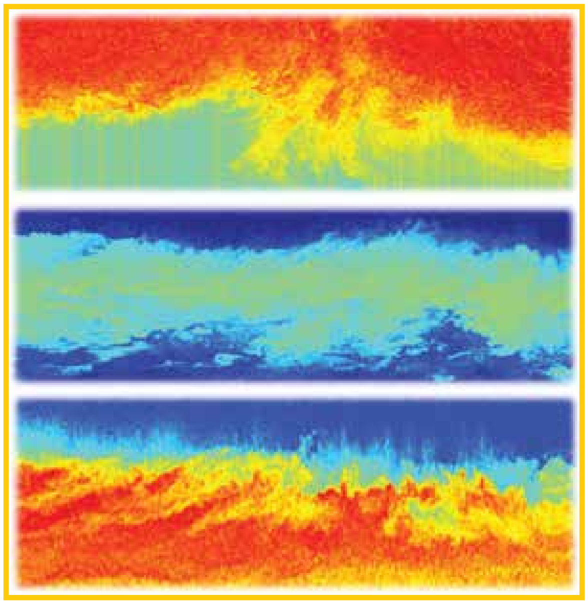


CAROLYN REYNOLDS received a Ph.D. in meteorology from Penn State University under the mentorship of Peter Webster, professor of meteorology, in 1993. Since then, she has worked at the Marine Meteorology Division in Monterey, California. She was global modeling section head at NRL from 2005 to 2014. Since 2014, she has been the lead scientist in the Probabilistic Prediction Research office, and she currently leads the NRL Monterey component of the Navy Earth System Prediction Capability effort. Her research interests include ensemble design, predictability, and various applications of adjoint-based diagnostics. She was an active participant in the DEEPWAVE field campaign. She is a fellow of the American Meteorological Society.

JUN MA is a scientist at Computational Physics, Inc., with expertise in dynamics and radiative transfer in the atmosphere. He works closely with colleagues at NRL in the development of the U.S. Navy's Navy Global Environmental Model numerical weather prediction (NWP) system, ground-to-space atmosphere-ionosphere model prototypes, and linear models and parameterizations of gravity-wave dynamics for naval NWP and research applications. Dr. Ma was an active participant in the DEEPWAVE field campaign, and he is now involved in scientific analysis and modeling of the DEEPWAVE field data.

NRL SCIENCE AS ART CONTEST

Radar Division Choice



Atmosphere Through the Eye of Millimeter-Wave Radar

These images of the atmosphere were taken by the NRL high-power 94 GHz millimeter-wave radar called WARLOC. Set up at the NRL Chesapeake Bay Detachment on the western shore of the Chesapeake Bay, the WARLOC system has at its heart a state-of-the-art 94 GHz gyroklystron developed by a team led by NRL. WARLOC supports investigation of a variety of Naval applications, including aircraft identification and precision tracking, but the NRL team realized early on that WARLOC also could be an unmatched cloud sensor. Other radars operate at 94 GHz, but the much higher power and antenna gain of the WARLOC radar enable it to detect lower reflectivity clouds at longer ranges and image the internal structure of visibly opaque clouds in tremendous detail.

Mai Ngo
Radar Division

Scaled Experiments of Explosion Decoupling

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Explosion Decoupling: Since 1961 there have been discussions in the literature as to how the detectability of an underground nuclear explosion might be reduced.[1–5] One technique, called decoupling, involves exploding the nuclear device inside an air-filled cavity whose radius is large enough so that the material outside the cavity wall reacts elastically to the explosion pressure. In this circumstance, the displacement at low frequencies measured by remote seismic sensors is thought to be as much as 300 times smaller than if the explosive had been emplaced with no surrounding cavity and in direct contact with the surrounding geologic material.[1,2] Recently, decoupling again has come to the fore as an issue affecting the capability of the international nuclear-test monitoring system to detect explosions proscribed by the Comprehensive Nuclear Test Ban Treaty.[6] There is only a small data set for understanding decoupling, so there are many uncertainties in predicting its effects and effectiveness.

A number of nuclear and explosive tests were performed decades ago to test the decoupling idea. In 1959, a series of chemical explosions in salt cavities was carried out. The series, called COWBOY, yielded decoupling factors — a measure of the reduction in detectability — between 14 and 73, depending on the cavity's scaled radius, i.e., the cavity radius divided by the cube root of the explosive yield.[4] In 1966, the STERLING nuclear explosion inside a salt cavity yielded a decoupling factor of 72, six times higher than that of a COWBOY explosion at the same scaled radius.[3,4] Ten years later, a nuclear explosion in a salt cavity in Azgir, at the same coupling radius as STERLING, yielded a decoupling factor not very different from that obtained with COWBOY.[4,5]

The uncertainties in predicting decoupling are related to a number of factors, including the limited accuracy of early codes; determining the appropriate constitutive models of the material outside the cavity at the depth of the explosion — in particular, the radius at which the material response becomes elastic; and incomplete knowledge of how a pressure wave propagates to a remote sensor through complex and often poorly known geology. Calibrating codes against nuclear experiments in materials other than salt, for which only two data points exist, is not feasible. Inferring nuclear decoupling from the results of chemical explosives experiments is suspect because nuclear and chemical explosions produce different pressure time histories.[7]

Scaled Experiments: Within certain limits, the accuracy of decoupling calculations and constitutive models can be checked against laboratory experiments. Such experiments allow for well-controlled environments, a large number of diagnostics, and variation of many of the experimental parameters at a reasonable cost. In our work, the consequences of an explosion inside an air-filled cavity under the earth's surface are partly duplicated in a laboratory experiment on spatial scales 1000 times smaller. The experiment measures shock pressures coupled into a block of material by an explosion inside a gas-filled cavity in that material (a typical cavity is shown in Fig. 1). The explosion is generated by suddenly heating a thin foil that is located near the cavity center with a short laser pulse, which turns the foil into expanding plasma, most of whose energy drives a blast wave in the cavity gas. A relevant characteristic of creating an explosion with sudden laser heating is that the specific energy of the explosion, i.e., the energy of the explosion divided by the exploding mass, is typically kilotons per kilogram, not unlike that of a low yield nuclear explosion. The explosion pressures and shock velocities are likewise comparable to those from nuclear explosions.

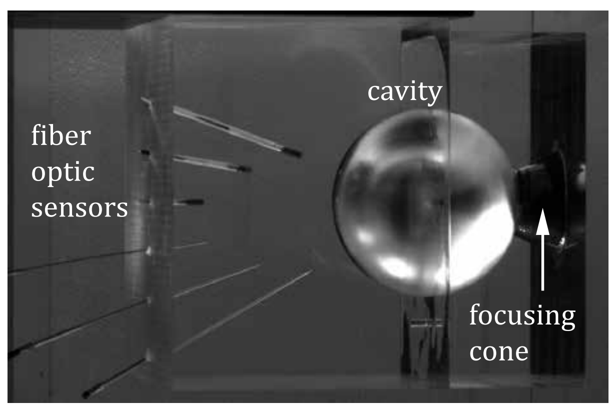

FIGURE 1
Photograph of an 8 cm diameter cavity inside a transparent block. A pulse from the NIKE krypton fluoride laser at the U.S. Naval Research Laboratory (1/2 mm diameter, 4 ns duration, 400 J to 1.6 kJ, 248 nm wavelength) is focused onto the surface of a thin foil at the cavity center through the conical structure at the right. Tubular structures on the left hold fiber-optic pressure and particle displacement sensors.

Shock pressures inside the block are measured directly with a Fabry-Perot fiber-optic pressure sensor. In addition, complementary measurements infer shock pressure from measurements of particle displacement made with a Michelson interferometer fiber tip sensor

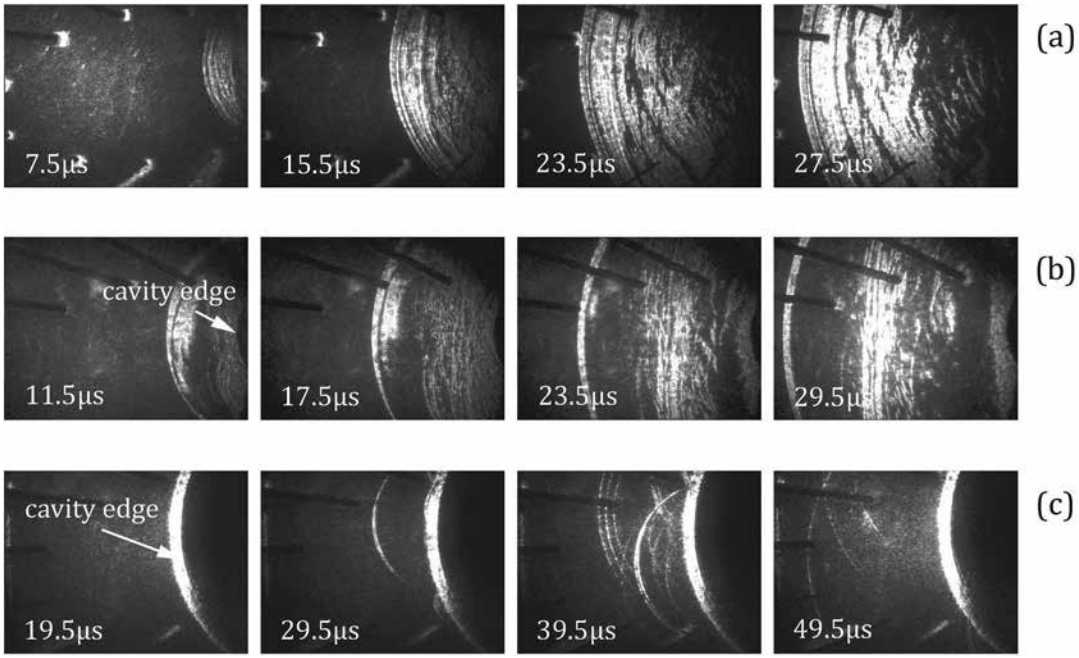

FIGURE 2
Shadowgraphs of shocks launched by a ~1.4 kJ laser pulse transmitted to polymethylmethacrylate (PMMA) from (a) 0.375 cm, (b) 2 cm, and (c) 5 cm radius cavities filled with 1 atmosphere of gas. Times after the laser strikes the target are shown. Edges of the cavity are marked in (b) and (c), but are not visible in (a). The tubular structures protruding from the left are fiber-optic sensors. Shocks launched from the smallest cavity are characterized by a sharp expanding front followed closely by motley structures representing additional pressure and relief waves launched as the blast wave rattles about the small cavity. The appearance of shocks launched from a 2 cm radius cavity are similar except that the sharp front and subsequent structure are clearly separate, which is presumably indicative of the delay between the launching of the first and subsequent shocks or relief waves from this larger cavity. Shocks from the largest cavity are qualitatively different. The initial hemispherical shock wave is absent, replaced by shocks that originate locally at different locations on the cavity wall. Also absent are the motley structures that follow the main shocks launched from smaller cavities. It seems that the blast wave in the largest cavity is too weak to launch a detectable shock into the block. Instead, we detect shocks launched locally by target debris hitting the cavity wall.

by applying the formula $P_s \sim \rho U_p U_s$, where P_s and U_s are the shock pressure and velocity, respectively, ρ is the density, and U_p is the particle velocity. In experiments with blocks that are transparent, the interpretation of probe traces is aided by dark-field-shadowgraphy images of the shock wave recorded as it propagates through the block (Fig. 2).

Results: Results from the experiments are modeled with the GEODYN code,[8–10] a massively parallel, Eulerian compressible solid and fluid dynamics code with adaptive mesh refinement capabilities,[9] developed at the Lawrence Livermore National Laboratory. The shock-capturing solver in GEODYN is derived from a high-order Godunov solver for fluid dynamics and is capable of handling extremely strong shocks and large deformations. The adaptive mesh refinement feature can be tailored to refine regions with high gradients and/or at material interfaces, in order to increase the level of detail where needed to maintain accuracy. Example calculation results are shown in Fig. 3. GEODYN has been previously validated, at large scales, for

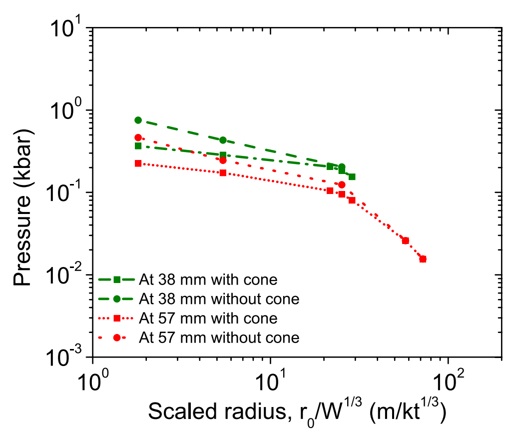

FIGURE 3
GEODYN calculated peak shock pressure vs scaled cavity radius at sensor locations of 38 mm and 57 mm from the explosion source. The cavity is filled with 1 atmosphere of gas. The "with cone" and "without cone" lines account for the effect of gas leakage out of the cavity after the target foil explodes and no longer provides an airtight barrier for the cavity air. Results show that air leakage is negligible for scaled cavity radii exceeding about 20 m/kt$^{1/3}$. For smaller cavities, air leakage reduces the coupled pressure, with the effect increasing as the cavity gets smaller; for the smallest (0.375 cm) cavity, the reduction in pressure is approximately 30%.

accuracy of its calculations and material models. We have shown that this code also accurately calculates our laboratory experiments, thereby providing a link between scaled laboratory experiments and full-scale phenomena of interest.

Detailed descriptions of the experiments and calculations, with a discussion of how these apply to full-scale explosions in cavities, are in Grun et al.[11]

Acknowledgments: The authors thank the crew at the NIKE facility at the U.S. Naval Research Laboratory, without whose expertise and dedication these experiments would not have been successful.

[Sponsored by the Defense Threat Reduction Agency]

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Two-Dimensional Sonic Prism

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Introduction: The emergence of autonomous systems such as unmanned undersea and aerial vehicles has led to the need for sonars with reduced size, weight, and cost compared to traditional systems. One way to address these new constraints is to utilize passive, analog apertures that are capable of replacing multi-active-element systems to achieve tasks such as beamforming. One example of an analog aperture is the leaky wave antenna (LWA), which has been explored extensively in the electromagnetic spectrum.[1] LWAs operate by using a coupling of direction-scanning capability and frequency, similar to a prism. Using this frequency steering, two-dimensional LWA geometries allow fully controlled two-dimensional steering of radiated sound with minimal hardware coupled to the LWA aperture.[2]

The concept of an acoustic LWA was first introduced at the U.S. Naval Research Laboratory in 2013 by Naify et al.[3] By using an analog aperture to provide steering direction, the electrical complexity and thus both weight and cost of the aperture are significantly reduced. The analog nature of the aperture also significantly reduces postprocessing computational load. This ability to control steering direction of acoustic waves has applications in a number of areas of naval importance, such as imaging, holography, and communications. The compact size and low-complexity robustness of an LWA make it ideal for small-scale systems such as hand-held sonars, unmanned underwater vehicles, and small acoustic modems.

Methods: Here, we demonstrate a realization of a two-dimensional acoustic leaky wave antenna developed for use in air.[4] The LWA was designed to allow steering of acoustic energy using only a single omnidirectional source transducer and a geometrically simple LWA aperture. The aperture was comprised of a two-dimensional parallel-plate waveguide patterned with an 11 × 11 array of sub-wavelength open shunts, which are illustrated in Fig. 4(a) and 4(b). The LWA dispersion properties and thus radiation angle of the acoustic energy in the surrounding fluid are determined by the design of the shunt and by waveguide geometry. The frequency-dependent steering angle, θ, of the LWA geometry was calculated using acoustic transmission line analysis. This angle is plotted as a function of frequency as arrows in Fig. 5. Finite element method simulation was used to verify directionality of the LWA and to calculate the expected sound pressure level (SPL) as a function of the frequency.[3]

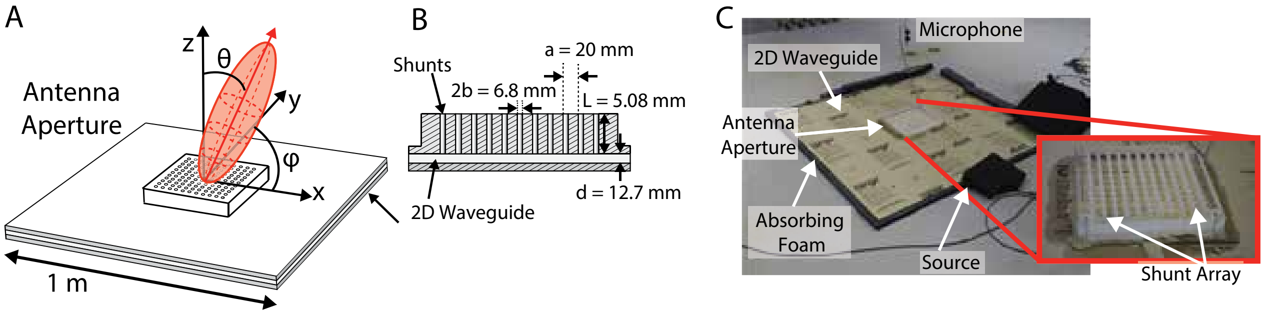

FIGURE 4
(a) Schematic of LWA defining radiation angles. (b) Cross-sectional schematic (xz-plane) of aperture and waveguide. (c) Photo of experimental setup indicating position of acoustic source, aperture, and scanning microphone.

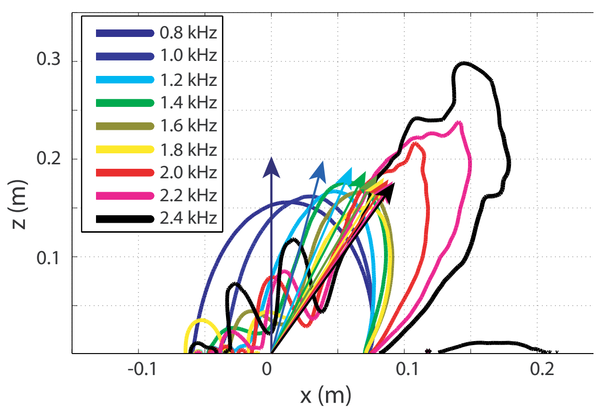

FIGURE 5
Finite element predicted sound pressure level (SPL) at value of 82 dB (curves) and predicted directionality using acoustic circuit analysis (arrows). SPL contour is taken in the xz-plane.

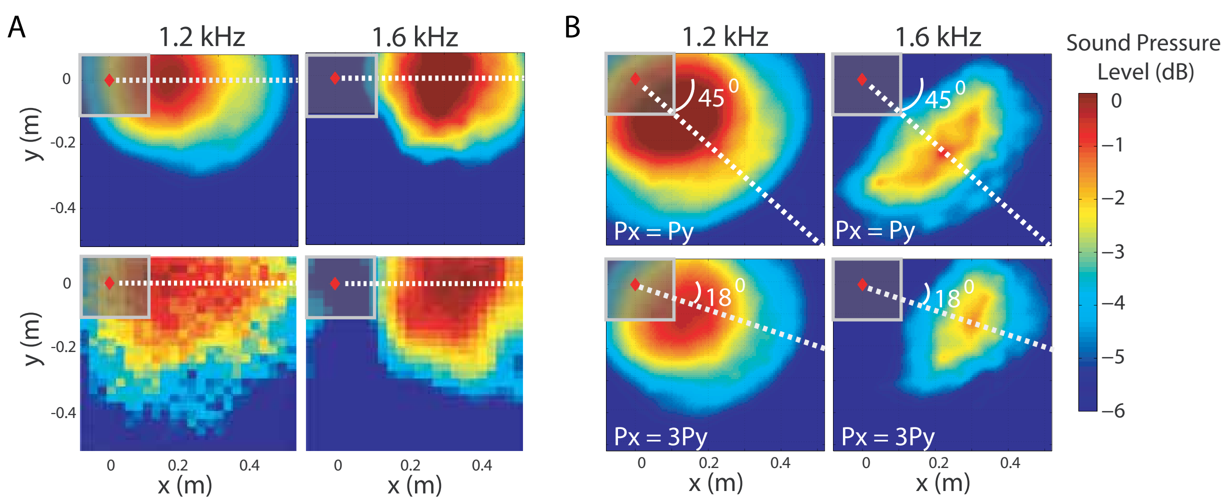

FIGURE 6
(a) Top: finite element predicted sound pressure level at a height of 0.5 m in the xy-plane. Bottom: measured sound pressure level. (b) Predicted beampatterns with varying magnitude of multiple input signals. Shaded box indicates location of antenna, white dashed lines indicate radiation direction φ.

The LWA was then constructed and the steering direction measured as a function of frequency and source pressure magnitude. The antenna was insonified using omnidirectional acoustic transducers mounted inside the waveguide. Radiated sound pressure level was measured using a microphone mounted on a three-axis positioning system. The top of the LWA structure was 0.5 m from the top of the antenna (see Fig. 4(c)) in the z-direction.

Results: Figure 6(a) (top) shows the predicted SPL on the xy-plane over a frequency range of 1.2 to 1.6 kHz. The shaded square indicates the location of the antenna and the white dashed line indicates the radiation axis. As the frequency of excitation is increased from 1.2 kHz to 1.6 kHz, the location of the radiation lobe peak is moved monotonically away from the center of the antenna. The total change in steering angle θ was approximately 20 degrees. Figure 6(a) (bottom) show the measured SPL, in the xy-plane.

The total dimensionality of controlled steering using an LWA is determined by both the geometry (i.e., a one- or two-dimensional waveguide aperture) and the number of sources. To expand the dimensionality of the steered beam to steer in φ as well as θ, up to four active transducers are used. Varying the pressure magnitudes Px and Py controls directionality in φ. This steering is demonstrated using finite element analysis in which two omnidirectional point sources are located inside the waveguide at (x,y) = (–0.5,0), called Px, and (x,y) = (0,0.5), called Py. Figure 6(b) shows the predicted beams steered using this method, with the dashed line indicating the radiation direction.

Since the frequency–angle relationship of the LWA is reciprocal, the aperture can also be used as a receive array for target localization. Additionally, since the dispersion relationship and thus effective frequency of the LWA is geometry-dependent, this type of device can be easily scaled to operate over a wide range of frequencies and can be used in sonar or medical ultrasonic applications.

[Sponsored by the NRL Base Program (CNR funded)]

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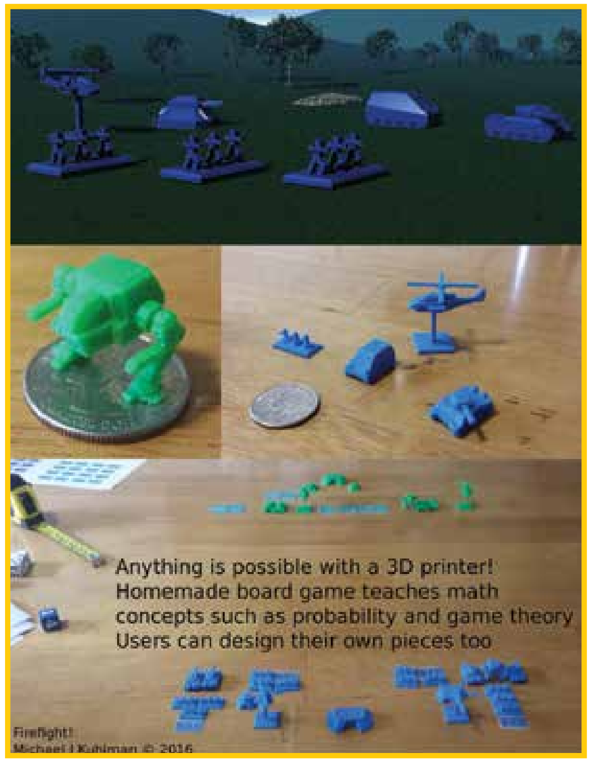
NRL SCIENCE AS ART CONTEST

Information Technology Division Choice



Firefight! A Homemade 3D Printed Board Game

Devising the original board game shown in this picture was a personal exercise for me in learning how to use computer-aided design software to create things for three-dimensional printing. It was also a lesson in how mathematics can play a role in decision making, even in something as fun as a tabletop game. The rules of the game are based on simple rules of probability, and each game piece plays a distinctive role, making tactical thinking key to a winning strategy. As an avid gamer, I am interested in the possible educational applications of this game, particularly as a tool for fostering more curiosity and learning about STEM subjects in young students.

Michael Kuhlman
Information Technology Division

Seasonal Forecasting of Northern Hemisphere Sea Ice Extent Using the Navy's Global Earth System Model

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Introduction: There is a need for subseasonal to seasonal predictions within the Department of Defense for mission planning. These predictions are between the typical weather forecast initial-value problem (e.g., 5 to 7 days) and the typical climate scales boundary-value problem (e.g., years to decades) and create a unique new forecasting paradigm in which atmosphere, ocean, sea ice, and other earth system components must be well-initialized and must well represent time-evolving physical processes.

The U.S. Navy is currently developing and testing a fully coupled, whole Earth system model for seamless predictions from days to months under the Earth System Prediction Capability (ESPC) national program. The current modeling setup includes a version of the NAVy Global Environmental Model (NAVGEM) atmospheric model designed for coupled integration, the HYbrid Coordinate Ocean Model (HYCOM) ocean model, and the Community Ice CodE (CICE) sea ice model (Fig. 1). The code base for HYCOM and CICE in the Navy Earth System Model is very similar to Global Ocean Forecast System (GOFS) 3.1, a pre-operational model used by the Navy to predict ocean and ice conditions using HYCOM and CICE as base models. NAVGEM had two main updates compared to the operational model. First, a modified Kain-Fritsch cumulus scheme[1] replaced the Simplified Arakawa-Schubert scheme to produce more realistic long forecasts of convection. Second, for consistency of the fluxes between the atmosphere and ocean, the air–sea boundary flux scheme was changed in NAVGEM to the modified COARE 3.0 scheme used in HYCOM.

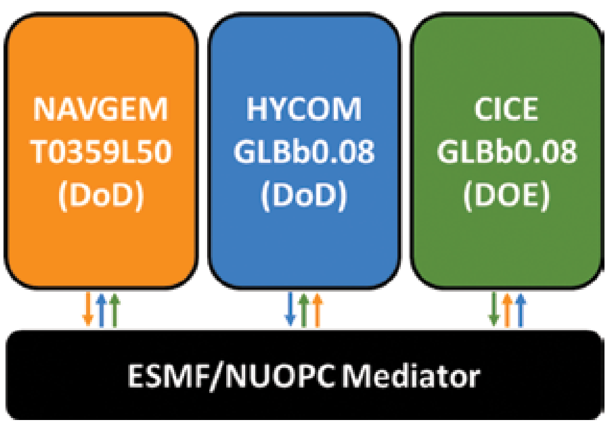

FIGURE 1
Description of the ESPC fully coupled model used for the Sea Ice Outlook (SIO) intercomparison project predictions. NAVGEM ran at the T0359L50 (~37 km, 50 levels) resolution, and HYCOM and CICE have ~3.5 km resolution at the North Pole. NAVGEM and HYCOM are Department of Defense (DoD)-sponsored models and CICE is a Department of Energy (DOE)-sponsored model. The mediator is developed by a joint sponsorship between multiple agencies using the National Unified Operational Framework (NUOPC) based in Earth System Modeling Framework (ESMF) tools. The mediator controls how the variables are passed between each model. The color arrows represent the variables from the respective component being passed to and from each component.

Sea Ice Outlook Forecasts: The Navy's Earth System Model has been in rapid development by the U.S. Naval Research Laboratory and partner organizations since 2013. In 2015, we included results in the Sea Ice Outlook (SIO), an international intercomparison project to predict the averaged Arctic September sea ice extent from forecasts using May, June, and July initial conditions.[2] Predictions submitted to the SIO by the Arctic research community include multiple techniques: dynamical models, statistical models, and heuristic models; the dynamical models include a mix of models used for operations and climate. These predictions aid in understanding sea ice predictability at subseasonal to seasonal timescales.

For the 2015 SIO, we ran 10-member time-lagged ensembles. The runs were initialized from operational NAVGEM and pre-operational GOFS 3.1 (i.e., HYCOM-CICE) for the last 10 days of each month at 12Z. HYCOM and CICE have an approximate resolution of 3.5 km near the North Pole and NAVGEM ran on the T0359L50 grid (~37 km horizontal resolution with 50 vertical levels).

Results: The observed mean September 2015 Arctic sea ice extent from the NASA ice team algorithm, which is used in the SIO reports, was 4.63 million km^2. For the Navy's Earth System Model ensembles, the mean (and range) of September Arctic sea ice extent were 5.6 (5.2 to 6.1), 4.6 (4.2 to 5.2), and 4.4 (4.2 to 4.8) million km^2 for the forecasts initialized at the end of May, June, and July, respectively. Results from all SIO contributions for the May, June, and July initialization had a median (and range) of 5.0 (3.3 to 5.7), 5.0 (3.3 to 5.7), and 4.8 (2.7 to 5.6) million km^2, respectively. For only the dynamical models, these contributions were 5.1 (4.4 to 5.7), 5.1 (4.2 to 5.7), and 5.0 (3.7 to 5.6) million km^2. Our June and July predictions were the closest to the NASA ice team observations when comparing against only the dynamical models.

Figure 2 displays the spatial variability of the mean September Arctic ice edge for the ensemble forecasts compared to the NASA ice team observations. The

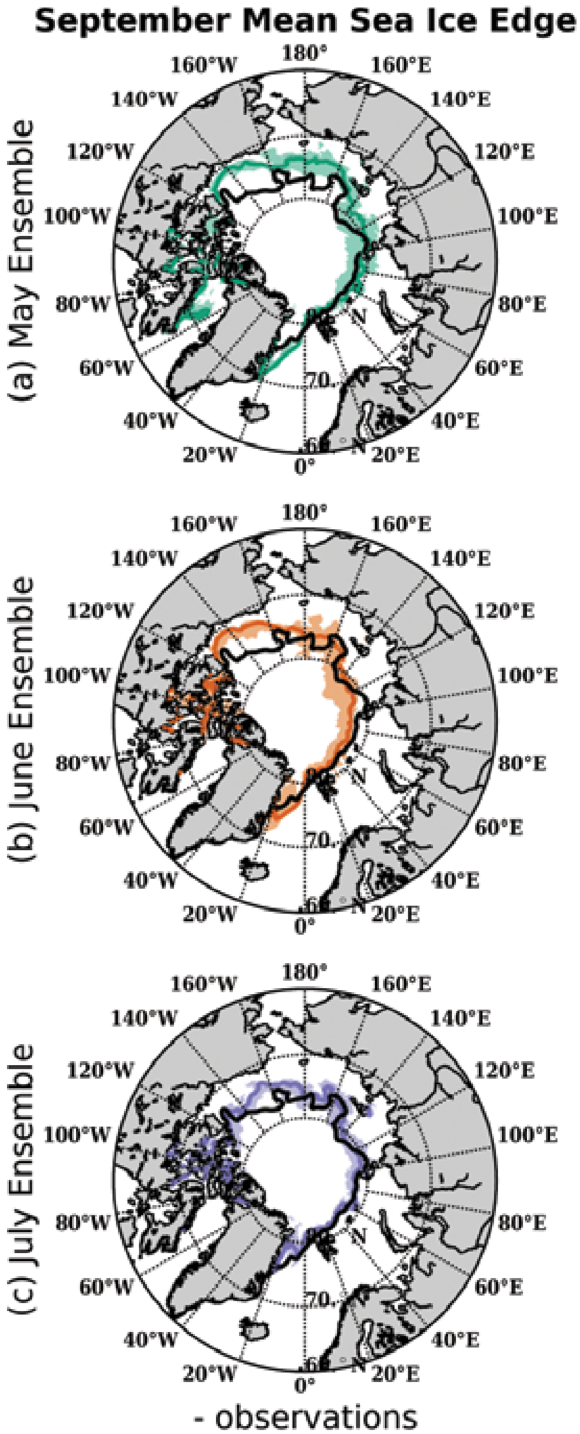

FIGURE 2
Arctic mean September sea ice edge defined by an average of 15% sea ice concentration from the (a) May, (b) June, and (c) July ensemble. The solid colored line represents the ensemble mean and the shaded region represents the spread in the sea ice edge. The black line corresponds to observations from the NASA ice team obtained from the National Snow and Ice Data Center (NSIDC).

mean predictive ice edge becomes more accurate with less forecast time, and the spread of the predictions generally becomes smaller at many locations. Figure 3 displays the time evolution of the Arctic sea ice extent from the ensemble runs compared to the NASA ice team observations. For all of these cases, the Navy's Earth System Model is losing sea ice at the beginning of the forecast, but melt rates become similar to the observations later in the forecast. This result may be due to different initial ice conditions used in operational NAVGEM and pre-operational GOFS 3.1 (i.e., HYCOM-CICE) that create inconsistences in the beginning of the forecast. Also note that there are differences between the NASA-derived ice extent and the initial ice extent in the model runs. The sea ice initial conditions for these runs are obtained from the GOFS 3.1 (i.e., HYCOM-CICE) pre-operational run, which is a different sea ice concentration product from the NASA-derived product. The GOFS 3.1 initial sea ice product detects more ice during the melt season and compares better to independent observations.[3]

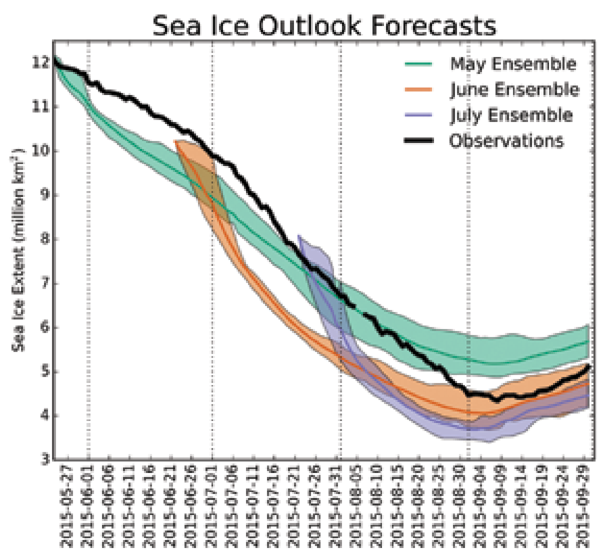

FIGURE 3
Arctic sea ice extent in million square kilometers from the forecasts that start in (green) May, (orange) June, and (purple) July ensemble runs. The dark color line represents the ensemble mean and the shaded region is the ensemble spread. The black line represents observations from the NASA ice team obtained from NSIDC. There are slight differences between the NASA observations and the initial forecasts because the modeling system uses a different ice concentration data set for initialization. The vertical dashed lines represent the first day of a month.

Summary: The Navy's Earth System Model for subseasonal to seasonal predictions is built on operational atmosphere (NAVGEM), ocean (HYCOM), and sea ice (CICE) dynamical models, with a few modifications to NAVGEM for boundary flux consistency and improved representation of extended-ranged convective processes. This coupled system has been in rapid development since 2013, and forecasts were submitted to the 2015 Sea Ice Outlook international intercomparison project to analyze the predictability of September

Arctic sea ice extent. Three 10-member ensembles were initialized at the end of May, June, and July, which corresponds to the June, July, and August SIO reports (https://www.arcus.org/sipn/sea-ice-outlook). Results from the Navy Earth System Model from the May ensemble were ~1 million km^2 larger than observations, but the June and July ensembles resulted in Arctic sea ice extent predictions that were the closest to observations when compared to the other dynamical models submitted to the SIO. Development is ongoing for the Navy Earth System Model, and initial results in this international intercomparison project are very encouraging.

[Sponsored by ONR]

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Tropical Sea Surface Temperature Retrieval Cold Biases Caused by Optically Thin Cirrus Clouds

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Motivation: Passive infrared satellite retrievals of sea surface temperature (SST) are assimilated by Navy models to optimize ocean analyses and coupled weather forecasts. SST retrieval algorithms designed for such measurements cannot screen all clouds, however, causing product error and subsequent cold bias that propagates through Navy models. Optically thin cirrus clouds (i.e., cold upper-tropospheric ice-phase clouds) are present 20% to 30% of the time globally. "Thin" refers to the translucent visual nature of the clouds. At cloud optical depths (COD) lower than 0.3, cirrus are highly transmissive, becoming practically invisible in passive infrared observations as COD approaches zero since emissions from the earth surface below the cloud overwhelm the signal measured from space. Tropical infrared SST retrievals are particularly susceptible to cirrus contamination, though, since cirrus are relatively cold targets (≤ −37 °C) propagating well above the warm sea surface waters found below the clouds.

Collocation of two NASA satellite datasets (MODIS, the Moderate Resolution Infrared Spectroradiometer on the Aqua satellite; and CALIOP, the Cloud Aerosol Lidar with Orthogonal Polarization flown aboard the CALIPSO satellite) allows us to estimate cirrus cloud contamination of split-window (11/12 μm) MODIS infrared SST retrieval products in the tropics. These products are the most commonly used Navy model assimilation product because they offer relatively high resolution (1 km × 1 km) and are available diurnally. Unlike passive sensors, though, lidars are active-based, using a laser to illuminate sources, measure backscatter, and profile target presence within the atmosphere. Collocating the lidar with the radiometer thus helps diagnose when cloud is definitively present. Using a radiative transfer model, contamination properties identified from the collocated MODIS/CALIOP products are are assumed constant across all passive infrared satellite platforms, including the two instruments and retrieval algorithms used by the Navy for SSTs (AVHRR and VIIRS). From this, cirrus-induced retrieval biases are estimated for each of their respective split-window SST products.

MODIS SST Product Contamination Due to Unscreened Thin Cirrus: MODIS and CALIOP fly in sequence approximately five minutes within one another in NASA's A-Train constellation of Earth-observing satellites. For 2012, MODIS 1 km × 1 km SST retrievals found within 1 km of the lidar track were collocated with the nearest 5-km CALIOP cloud profile retrieval (14 such pixels per lidar observation). Approximately 28% of the SST retrievals investigated were contaminated with cloud. Of that sample, nearly 90% (25% absolute) were due to optically thin cirrus (Fig. 4). The average cirrus cloud optical depth was approximately 0.04, which is very near the subvisual threshold for clouds whereby they would not even be visible to an observer on the ground. This result is highly consistent, however, as cirrus cloud occurrence is exponentially more common globally at extremely low optical depths. Ice crystals are far more persistent and long-lasting than liquid water droplets and can be propagated hundreds of kilometers downwind after being nucleated, which leads to very diffusive cloud formations.

SST Bias Estimates Across MODIS, AVHRR, and VIIRS: Using a radiative transfer model, MODIS,

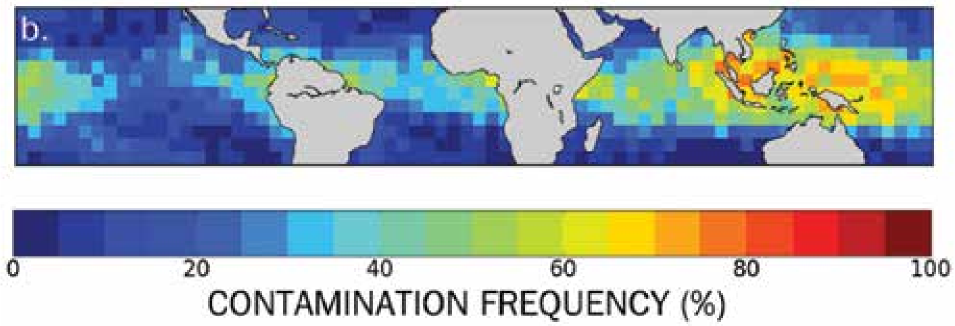

FIGURE 4
Relative frequencies of NASA Aqua-MODIS satellite split-window infrared SST retrieval contamination during 2012 due to cirrus cloud presence identified with collocated NASA CALIOP lidar observations.

AVHRR, and VIIRS split-window infrared SST retrievals were modeled (each uses slightly different channels and bandwidths). A cirrus cloud was placed within the model radiative column, 1.5 km thick, in 250 m segments between 10 and 18 km above sea level. This roughly corresponds with the depths of the tropical atmosphere where cirrus clouds propagate. Further, the cloud optical depth was varied in 0.01 segments between 0.01 and 0.30, thus simulating the physical nature of optically thin cirrus. The corresponding cold bias solved for each segment, representing the potential for cloud presence, was then built into a "cold bias matrix" for each instrument (MODIS is shown in Fig. 5). Assuming cloud contamination consistent across the three instruments (relative cloud occurrence frequencies from MODIS are superimposed in Fig. 5), we then integrated the matrices relative to actual contamination characteristics observed in the tropics and estimated cold biases for each satellite.

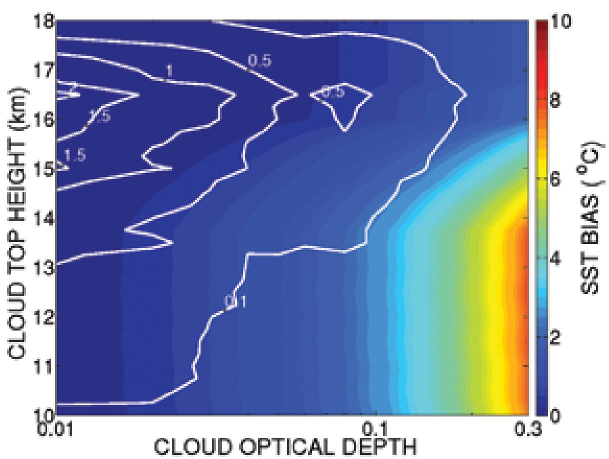

FIGURE 5
Radiative transfer model simulations of potential SST retrieval cold bias for any unscreened optically thin cirrus cloud corresponding with the given cloud top height and optical depth for the MODIS split-window algorithm. Overlaid on each composite are relative Aqua-MODIS/CALIOP collocated cirrus contamination percentage occurrence frequencies (%).

We estimate "absolute" mean SST cold biases between 0.09 and 0.14 °C for MODIS, VIIRS, and AVHRR (Table 1, next page), the latter two being operational sensors used for assimilation by the Navy. "Absolute" in this context refers to the bias anticipated in bulk-averaged SSTs, since the phenomenon only occurs approximately 25% of the time. The "relative" mean cold bias, however, which relates to any single contaminated observation, varies from 0.37 to 0.53 °C. This value is much higher than the stated uncertainty presently parameterized within Navy models assimilating operational infrared SST products (±0.2 °C). Since this latter term was designed to account only for simple retrieval noise, the result is a critical new product/assimilation error term that takes into account the potential for unscreened thin clouds that are in fact pervasive within these products. This study will therefore improve skill and accuracy across coupled Navy ocean and weather models for improved system prediction.

Acknowledgments: This work was conducted in part through the Naval Research Enterprise Internship Program (NREIP), through which JWM spent ten weeks working at NRL Monterey during summer 2015. JRC acknowledges the support of NASA on behalf of the CALIPSO Science Team.
[Sponsored by NASA]

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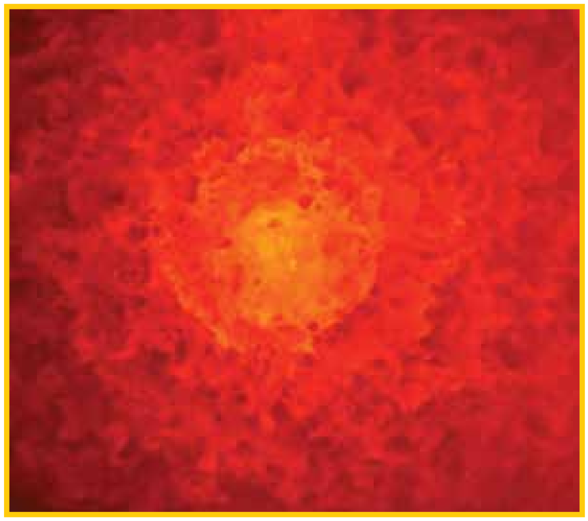
TABLE 1 — Mean absolute (relative) optically thin cirrus cloud cold biases in MODIS, AVHRR, and VIIRS SST retrievals from radiative transfer model simulations (Fig. 5), and assuming quality-assured Aqua-MODIS/CALIOP collocated contamination characteristics, segregated globally and respectively for the Atlantic, Indian, and Pacific Ocean basins.

SENSOR	GLOBAL	ATLANTIC	INDIAN	PACIFIC
MODIS	0.13°C (0.49°C)	0.11°C (0.53°C)	0.14°C (0.49°C)	0.13°C (0.46°C)
AVHRR	0.13°C (0.49°C)	0.11°C (0.53°C)	0.14°C (0.49°C)	0.13°C (0.46°C)
VIIRS	0.10°C (0.40°C)	0.09°C (0.45°C)	0.11°C (0.39°C)	0.11°C (0.37°C)

NRL SCIENCE AS ART CONTEST

Optical Sciences Division Choice



The Eye of Sauron

The imagery was recorded with a mid-wave infrared camera pointed down at the surface of a body of water. The camera is sensitive to temperature fluctuations in the skin (the uppermost surface layer, usually only a few microns thick) of the surface. The fluxes in temperature are caused by jets of warm water coming to the surface and spreading. The artistic value of the imagery was recognized immediately upon the review of the raw data, as NRL scientists found it hard to stop staring at the recording. The image is called The Eye of Sauron for its resemblance to the title character and main antagonist of J.R.R. Tolkien's *The Lord of the Rings*.

Ivan Savelyev and Peter Judd
Remote Sensing Division

Organic Nanotubes: Protein Encapsulator, Concentrator, Protector

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[1]*Chemistry Division*
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Introduction: Water soluble tubular nanoarchitectures comprised of nanochannels with dimensions comparable to the sizes of biomacromolecules have great potential as nanocontainers to encapsulate and stabilize biomacromolecules in aqueous solution. The enhanced stabilities of encapsulated biomacromolecules, such as proteins, arise from the restriction of the unfolding of proteins under confinement. We use lithocholic acid (LCA), one of the naturally occurring bile acids, to form nanotubes in aqueous solution via self-assembly (Fig. 1). Formed nanotubes have inner diameters ranging from 20 to 40 nm, and we can use them to encapsulate proteins under biologically friendly conditions.

Protein Encapsulation and Concentration: We have encapsulated, respectively, a green fluorescent protein, eGFP,[1] and an enzyme, horseradish peroxidase (HRP),[2] inside LCA nanotubes by adding eGFP or HRP solution into nanotube suspensions. The encapsulation of proteins is achieved via, initially, the driving force of concentration gradient, followed by the adsorption of the protein molecules on the inner surface of the nanotube wall. We confirm the encapsulation of eGFP and a custom synthesized HRP–Alexa Fluor 488 (dye) enzyme conjugate using confocal fluorescence microscope imaging of the LCA nanotubes collected from mixtures of nanotubes and proteins. Before imaging, nanotubes are thoroughly cleaned to remove all protein molecules attached to the outer surface of the nanotubes. The green fluorescence shown in Fig. 2 confirms the encapsulation of the HRP–Alexa Fluor 488 enzyme conjugate inside the nanotubes.

To understand the environment surrounding the encapsulated protein molecules, i.e., the extent of confinement or crowding inside the nanotubes, we use fluorescence resonance energy transfer (FRET) imaging microscopy to obtain the mean distance between proteins, based on Förster's theory. By comparing the mean distance between protein molecules encapsulated inside the LCA nanotubes to the mean nearest neighbor distance in the initial protein solution, we derive a concentration factor as high as 480 times greater resulting from the encapsulation, demonstrating that the LCA nanotubes act as highly efficient protein encapsulators and concentrators.

Behaviors of Proteins Inside the Nanotubes: We use confocal fluorescence microscopy to study the release rate of encapsulated proteins from nanotubes by monitoring the change in average fluorescence intensity of individual nanotubes immersed in a buffer solution free of any protein. In contrast to the relatively rapid encapsulation of protein into the nanotubes, the release rate is very slow at room temperature. In addition to characterizing the release behavior for encapsulated protein from the inner volume of the nanotubes to the surrounding aqueous environment, we study the transportation behavior of proteins within the nanochannel of the nanotubes. Fluorescence recovery after photobleaching (FRAP) is an effective method for assessing

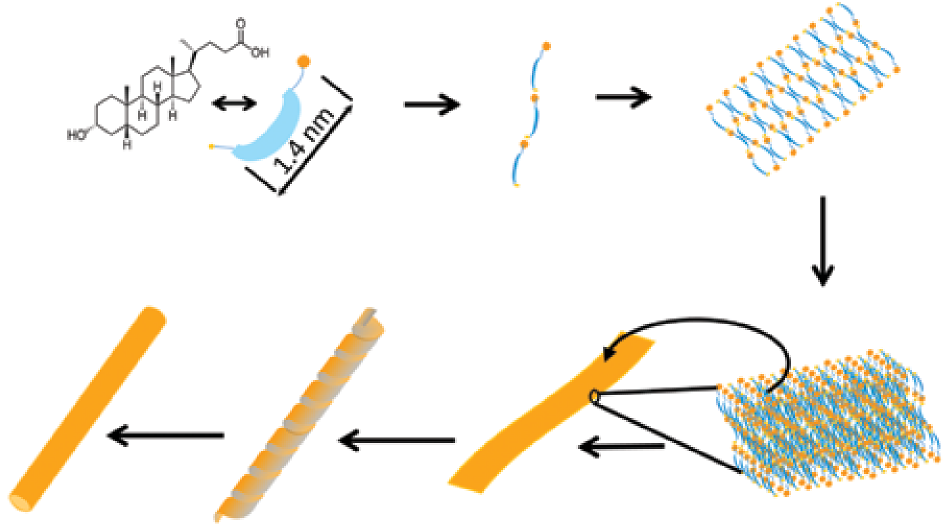

FIGURE 1
Schematic showing hydrogen bonding and hydrophobic interactions among LCA molecules, and their self-assembly into nanotubes.

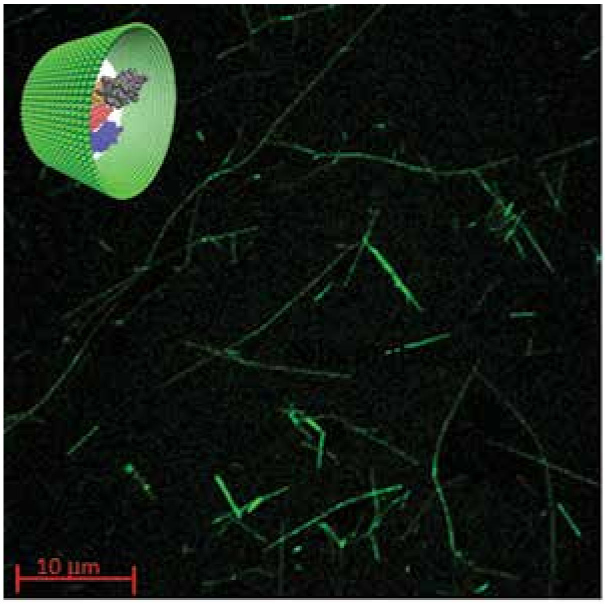

FIGURE 2
Confocal microscope image of Alexa Fluor–labeled HRP encapsulated in LCA nanotubes. Inset shows a schematic of a simulation setup for protein inside a 20 nm nanotube.

this transport. The FRAP results are in agreement with the results obtained in the release rate studies: the transportation of protein within the nanotube is very low and there is little if any recovery in fluorescence intensity 60 min after photobleaching. Molecular dynamics simulations support the experimental findings: under the attractive nanotube wall condition, the diffusion of an eGFP molecule can be slowed by as much as three orders of magnitude when compared to an eGFP molecule in bulk solution. Additionally, if the interaction strength, ε, is greater than 0.5 kcal/mol, some portion of eGFP molecules are immobilized on the inner surface of the nanotubes.

The confined and crowded environments inside LCA nanotubes enhance the chemical and thermal stability of encapsulated eGFP and HRP. Under conditions of high concentration of chemical denaturant and elevated temperature, encapsulated eGFP retains more than 70% of its fluorescence intensity after three hours, while free eGFP loses more than 70% of its fluorescence intensity (Fig. 3 (a)). Encapsulated HRP retains its catalytic activity despite being heat-treated for as long as 14 h at 55 °C. In contrast, the catalytic activity of free HRP drops more than 80% (Fig. 3 (b)).

The amount of HRP encapsulated in LCA nanotubes increases dramatically when the mixture of HRP and LCA nanotubes is brought to an elevated temperature. Within 4 h of thermal treatment at 55 °C, the amount of HRP encapsulated by the LCA nanotubes is more than 4 times the amount of HRP encapsulated when equilibrated at 4 °C for 7 days. Molecular dynamics simulations show that the higher degree of exposure of hydrophobic residues in HRP at elevated temperatures enhances the hydrophobic interaction between HRP and the nanotube wall, resulting in the increased amount of HRP surface adsorption and, hence, the overall amount of encapsulation inside the nanotubes.

Summary: The nanospace inside organic nanotubes provides a confined and crowded environment that protects proteins against chemical and thermal denaturation, and preserves enzyme catalytic activity following prolonged elevated temperature exposure. Enhanced thermal stability and high encapsulation capacity derived from LCA nanotubes are highly desirable characteristics in Navy applications that involve proteins under harsh environmental conditions.

[Sponsored by the NRL Base Program (CNR funded)]

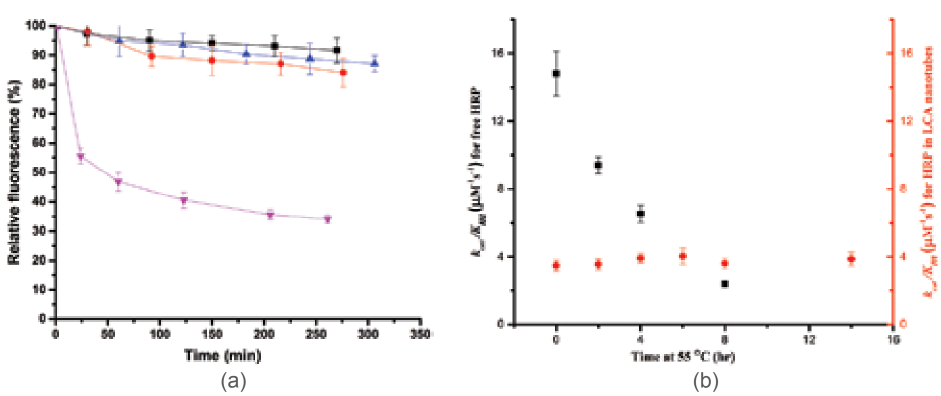

FIGURE 3
(a) Chemical denaturation in 6 M urea at pH 7.4 of free eGFP (magenta inverted triangles) and eGFP encapsulated in LCA nanotubes with initial equilibrating concentrations of 6 μM (black squares), 30 μM (blue triangles), and 90 μM (red circles). (b) k_{cat}/K_m (an indicator of catalytic efficiency) vs exposure time at 55 °C for free HRP (black squares) and HRP encapsulated in LCA nanotubes (red circles).

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Smart Bandage for Acute Care Covering of Severely Injured Limbs

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Introduction: Traumatic limb injuries pose a significant threat to the warfighter on the battlefield, particularly when such wounds are sustained far from medical facilities. In the absence of immediate medical treatment, paramount functions for a field-applied wound dressing material are hemorrhage control, infection prevention, and preservation of tissue viability. In this context, the capabilities of any single, currently available commercial wound dressing technology are insufficient, especially for extended use (up to 72 hours). Therefore, a team from the U.S. Naval Research Laboratory and the Naval Medical Research Center is following a polymeric materials approach to design and develop an innovative, multifunctional wound-contact material to preserve tissue viability and increase survivability by controlling hemorrhage and infection in traumatic combat wounds. The concept, shown in Fig. 4, incorporates numerous medical functions into a single "smart" polymer material that is both physically robust to withstand the rigors of military use and able to automatically activate multiple functionalities upon contact with the wound.

Polymer Synthesis: A series of hybrid polymeric hydrogel foams ranging in composition were synthesized and characterized for their ability to serve in a unique multilayered material that demonstrates physical robustness, absorption and hemostatic capabilities, and controllable drug release kinetics. A novel block-copolymer hydrogel consisting of stimuli-responsive poly(N-isopropylacrylamide) (PNIPAM) block covalently linked to polyethylene glycol (PEG) crosslinked poly(sodium and calcium acrylate) was designed and synthesized in two steps via established methods.[1] The composition was modulated to engineer materials that can regulate responses to thermal and pH stimuli, and can moderate drug release and exudate absorption. In an effort to maximize polymer-wound contact, open-celled porous networks with tunable mechanical properties were fabricated. Such controllable open-cell microporous structures are achieved (Fig. 5) by employing high internal phase emulsion (HIPE) techniques to yield high surface areas that are beneficial for exudate absorption, drug release, and hemostasis. The polyurethane hydrogel foam materials also exhibit increased mechanical integrity and durability.

Material Properties: Several methods were employed to characterize these materials in the context of a wound dressing application, specifically to measure thermal and mechanical stability, wound exudate absorption capacity, and drug release kinetics. Through thermogravimetric analysis, differential scanning calorimetry, and dynamic mechanical analysis, we demonstrated that the hydrogels are thermally and mechanically stable in a range of environmental conditions (i.e., thermal degradation temperatures in the range of 150 to 250 °C) to ensure they are ideal for field use, transit, and storage. Rates of exudate absorption were simulated with pH 7.4 buffer solutions (similar to blood pH) and found to equal or exceed the performance of comparable commercial materials. For the poly(acrylic acid)-based HIPE gels, exudate absorption capacity is found to be inversely proportional to the amount of cross-linker employed, whereas exudate absorption rate increases with porosity, which scales with calcium acrylate content. In polyurethane-based hydrogels, absorption capacity is correlated to average pore size of the foam, which is tuned via biocompatible nonionic surfactants. Identification of such structure–property relationships allows us to tune the performance of the materials via polymer chemistry to meet the extreme demands of the field deployable environment.

Delivery of antimicrobials and therapeutics to the wound site is a central functionality of this wound dressing material. Drug release kinetics of broad spectrum antimicrobials such as cefazolin and gentamicin were monitored by high performance liquid chromatography. Elucidation of drug release kinetics confirmed that antimicrobial release from the hydrogels was primarily controlled via diffusion and swelling behavior of the hydrogels, both of which ultimately depend on the chemical composition. We determined that cross-linking density significantly affects drug release kinetics; therefore, by tuning the polymer structure, we are able to achieve burst release kinetics. The bolus release of an antimicrobial from the synthesized dressing to the wound site will prevent bacteria from

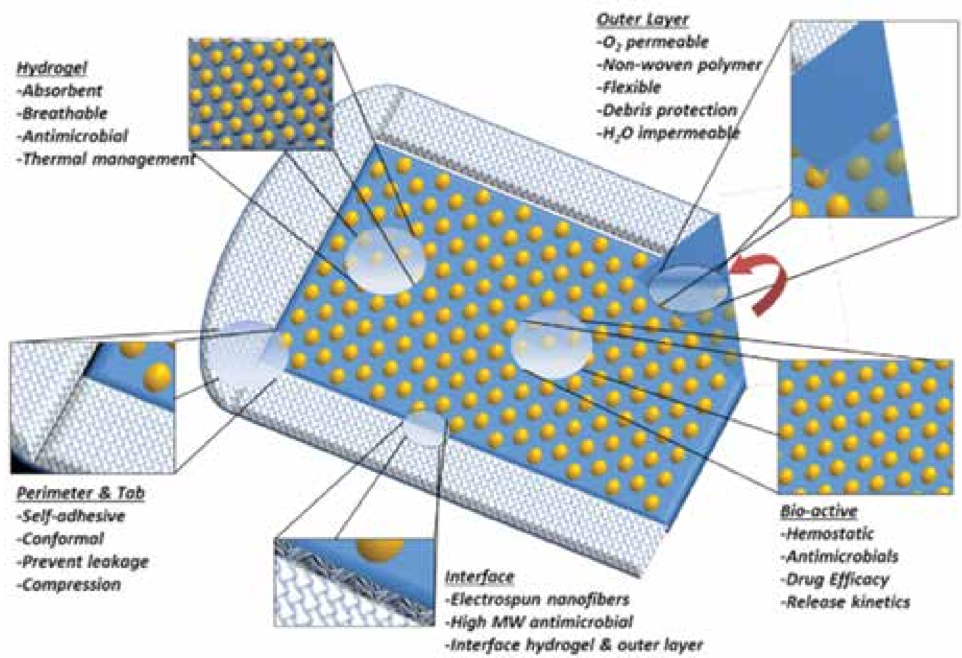

FIGURE 4
Conceptualized image of multifunctional wound dressing composite.

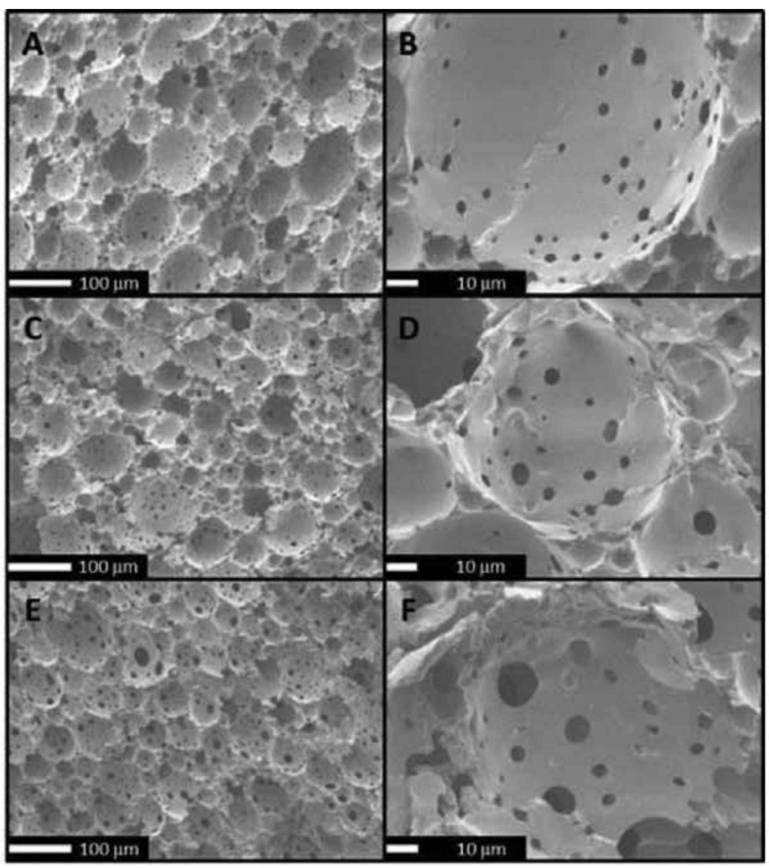

FIGURE 5
Scanning electron micrographs showing typical polyHIPE morphology and variation of void and pore size depending on calcium diacrylate content (10 wt% PNIPAM, 20 mol% PEGDA). A and B: 0.1 equiv., C and D: 0.2 equiv., E and F: 0.3 equiv.

colonizing and infecting the wound bed during the 72-hour window. Stimuli-responsive drug release will be complemented by biostatic properties of the composite wound dressing provided by electrospun fibers with nonleaching tethered biocides.[2]

Biotesting: Wound-dressing relevant biological testing comprising blood coagulation, zone of inhibition, cytotoxicity, and antimicrobial efficacy assays evaluated the performance of our polymeric hydrogels. Preliminary coagulation studies performed on whole blood with the polymer structure alone suggest innate hemostatic character, even prior to the incorporation of additional hemostatic compounds. Zone of inhibition testing against both Gram-positive and Gram-negative bacteria cultures confirm that the polymeric materials are capable of delivering antimicrobials when loaded with therapeutics. Initial cytotoxicity studies with HeLa cells indicate that the polymeric materials are biocompatible and exhibit reduced cellular adhesion without toxic effects. Through our collaboration with the Naval Medical Research Center, our materials are being evaluated within more realistic in vivo model systems (murine and porcine wound models) via an iterative improvement process.

Summary: We are developing a multifunctional wound-dressing material through polymer synthesis, material characterization, and performance testing designed specifically to increase survivability of future warfighters from severe wound trauma that occurs in remote areas of the world, far from medical facilities.

Acknowledgments: The authors thank C.G. McGann, ASEE postdoctoral associate at NRL, for his assistance in mechanical characterization. NRL Chemistry Division performed material development and preliminary testing. The Naval Medical Research Center performed in vivo biological evaluations of materials.

[Sponsored by ONR Future Naval Capabilities]

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Exploiting Microbial Machines for Chemical Warfare Agent Remediation

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[1]*National Research Council Research Associate*

[2]*Center for Bio/Molecular Science and Engineering*

Introduction: Microbes from all branches of life release small proteoliposomes, known as outer membrane vesicles (OMV), into their surrounding environment. These nanoscale structures are comprised of diverse biomolecules such as phospholipids, glycoproteins, and lipopolysaccharides and can be filled with proteins, nucleic acids, and small molecules. Their function is as diverse as their composition, with vesicles being implicated in cell–cell communication, host defense mechanisms, and pathogenesis. Here we show that through the development of genetic constructs, we can direct a recombinant protein, specifically an enzyme for the remediation of organophosphate compounds, into bacterial outer membrane vesicles. We demonstrate this as a viable method of increasing protein yield, stabilizing the recombinant enzyme for long-term storage and delivery, and developing reagents that can be used for the remediation of organophosphate compounds in contaminated water samples. The technology being developed will allow for enzymes and other cargo to be interchanged, facilitating the development of novel bioderived reagents for environmental remediation/decontamination.

OMV Loading Strategy: Due to the diverse functions that OMV serve in a bacterial community, the exact mechanisms that control OMV biogenesis are not well understood. To circumvent the need to elucidate the mechanisms, a synthetic bioconjugation strategy was developed to facilitate OMV loading. Two separate plasmids were utilized to simultaneously express a mutant transmembrane porin protein (OmpA), known to be present in high abundance in OMV, and a mutant enzyme (phosphotriesterase, PTE). Each protein is expressed as a fusion construct to complementary components of a SpyTag/SpyCatcher (ST/SC) split protein bioconjugation system. When both the OmpA-ST and PTE-SC are in close proximity, the ST and SC domains undergo isopeptide bond formation, effectively tethering the enzyme to the inner surface of the bacterial outer membrane (Fig. 6).[1] As OMV are released from the outer membrane, the tethered enzyme is drawn into the vesicle, facilitating packaging.

In the absence of the bioconjugation system, intracellular production of the non-endogenous enzyme at high levels is toxic to the bacteria, which results in a reduction in proliferation and vesiculation (Fig. 7(a), PTE

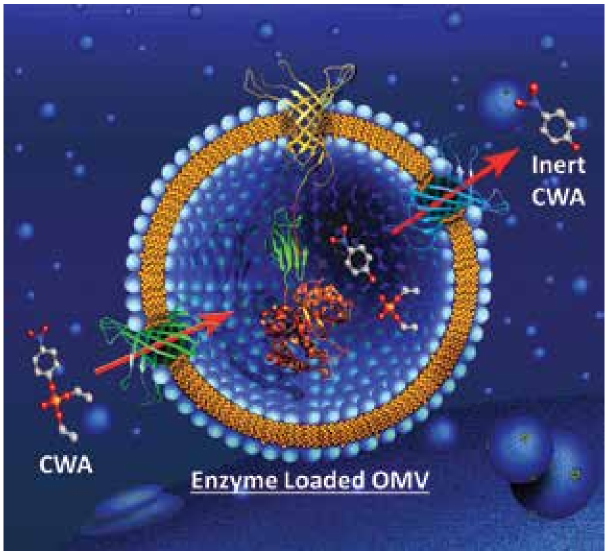

FIGURE 6
Schematic representation of a chemical warfare agent (CWA) undergoing an enzymatic cleavage within an enzyme-loaded outer membrane vesicle (OMV) releasing an inert degradation product. This functions as a "cell-free" nanobioreactor, eliminating the need for harsh chemical based CWA remediation techniques.

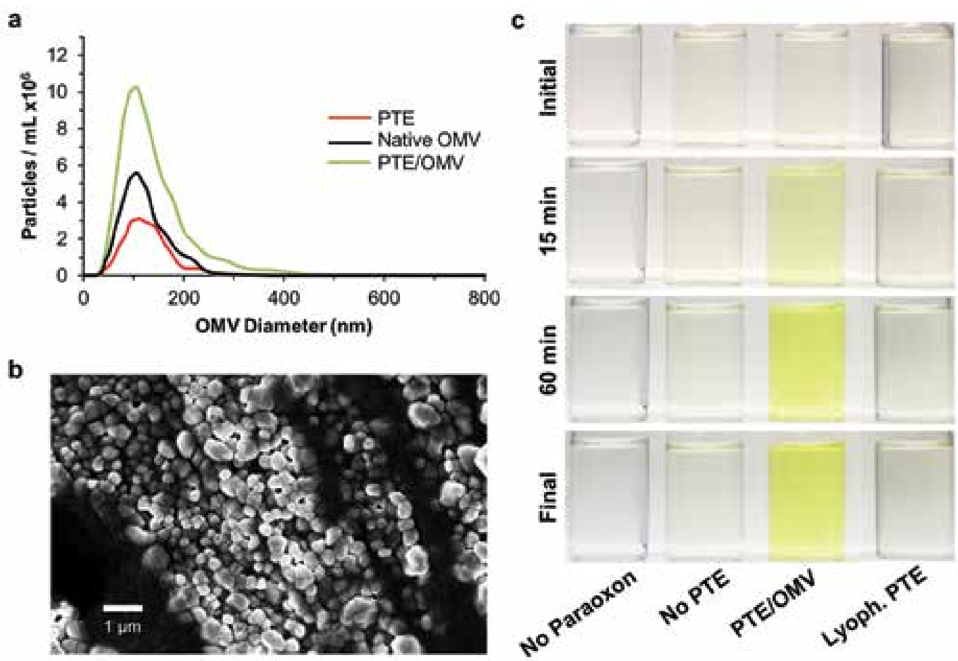

FIGURE 7
(a) Coexpression of OmpA-ST and encapsulated enzyme (PTE-SC) increases overall vesiculation while improving overall enzyme production without impacting OMV size distribution (PTE/OMV) compared to OMV purified from PTE expressed alone (PTE) and Native OMV. (b) SEM image of lyophilized, enzyme-loaded, bacterial OMV. (c) Remediation of paraoxon, a highly toxic pesticide, utilizing lyophilized PTE-loaded OMV. The yellow color is indicative of the paraoxon degradation product, p-nitrophenol, signifying successful remediation.

trace). Utilizing the synthetic linkage strategy to load OMV with enzyme provides the bacteria with a mechanism to export the toxic PTE, resulting in an increase in both enzyme and vesicle production by more than 4-fold and more than 2-fold, respectively (Fig. 7(a), PTE/OMV trace).[1] The facilitated incorporation of PTE within the OMV also resulted in a 2-fold increase in packaging efficiency compared to expression of PTE in the absence of the bioconjugation system. By packaging the enzyme within the protective environment of the OMV, we also observe a significant increase in enzyme stability to prolonged storage at elevated temperatures, freeze-thaw cycles, and lyophilization.

Chemical Warfare Agent (CWA) Remediation: By purifying the OMV from the bacteria, the enzyme-loaded vesicles can be utilized as a cell-free reagent for environmental remediation applications, eliminating the need for harsh chemical based remediation protocols (Fig. 7(b)). In this model system, PTE was selected as the OMV packaged enzyme for the remediation of paraoxon-contaminated water. Paraoxon is a highly toxic organophosphate-based pesticide that is often used as a sarin/VX chemical warfare agent simulant. To demonstrate a proof-of-concept remediation, lyophilized PTE-loaded OMV were added to a paraoxon-contaminated water sample and compared to lyophilized free-PTE (Fig. 7(c)). The lyophilization process inactivated the majority of the free-PTE, while the lyophilized PTE/OMV remediated all paraoxon in just over an hour at room temperature. Representative of the improved stability, the OMV/PTE reaction was given a second bolus of paraoxon after four days of storage at room temperature. The encapsulated PTE exhibited >60% retained activity for this second remediation cycle.

Future Directions: Further research is being conducted using PTE-loaded OMV in real-world paraoxon-contaminated water sources such as streams, ponds, oceans, rainwater runoff from building structures, and parking lots. The proof-of-concept packaging of PTE within OMV and subsequent stability and remediation enhancements observed using these cell-free nanobioreactors demonstrates a promising beginning to developing more environmentally friendly remediation strategies. Alternate applications involving the packaging of different enzymes, as well as multiple enzyme systems, are also currently being explored across various environmental remediation, microbial community control, and therapeutic applications.[2]

[Sponsored by ONR]

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Electronics and Electromagnetics

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Tactical Electronic Warfare Division Choice

Starry Knight Single-Person-to-Orbit Reusable Spacecraft Concept

This poster illustrates the Starry Knight conceptual design for a reusable launch vehicle (RLV), a small launch system capable of launching a payload into space more than once. The Starry Knight RLV would carry either one passenger along with lightweight instrumentation and secondary payloads or, in the case of an unmanned flight, a supply payload of weight equivalent to a manned flight. The front section is detachable for controlled reentry and glide to recovery airstrip. Orbital RLVs are thought to provide the possibility of low cost and highly reliable access to space compared to the time and expense of converting heavy lifting expendable launch vehicles.

Sean Bain and Richard Foch (deceased)
Tactical Electronic Warfare Division

Efficient Radar Cross Section Prediction at Millimeter-Wave Frequencies

S.M. Rao and M.S. Kluskens
Radar Division

Introduction: The objective of this research is to develop an ultrafast, accurate algorithm for the prediction of radar cross section (RCS) of Navy ships, subsystems, shipboard antennas, and other large objects at millimeter-wave frequencies (30–300 GHz). In this frequency range, most Navy platforms are considered to be electrically large objects because of their physical size. This means that the surface area of the given body spans several thousand square wavelengths. The popular method of moments (MOM) technique,[1] which is used to handle similar problems at lower frequencies, is prohibitively expensive in terms of computational and memory requirements and hence is not practical in this frequency range. We present a new method to efficiently predict the RCS of large objects at millimeter frequencies.

Description of the New Method: In the conventional MOM algorithm, the target surface is approximated via planar triangular patches when applied to a perfectly conducting (PEC) target. The triangular patch-modeling scheme is preferred since an arbitrary body can be approximated with minimum modeling error. Then, Rao-Wilton-Glisson (RWG) functions,[2] which are defined over the triangular domains, are used to represent the electromagnetic currents on the surface of the target. They are referred to as basis functions since they form the basis for the electromagnetic scattering solution, and the resulting electromagnetic equations represent the fields generated by the surface currents. Next, the electromagnetic boundary conditions on the surface of the target are enforced utilizing RWG functions, which are also used as testing functions, thus generating a symmetric, square MOM matrix of size N that is more amenable to numerical processing. Note that N represents the total number of basis/testing functions in the numerical solution scheme and must be chosen such that there are 300 to 400 functions per square wavelength surface area. Also, note that the computer storage and processing time for the MOM solution are proportional to N^2 and N^3, respectively. For electrically large objects spanning a few thousand wavelengths, in millimeter frequency range N can be over a million and the storage and solution times are beyond the capabilities of present day computers. The new procedure described here drastically reduces these requirements and enables the accurate solution in a simple way.

In the new procedure, the first step involves approximating the given structure via the triangular patch scheme and using RWG functions as the basis and testing functions as in the conventional MOM solution. The next step involves gathering the basis functions into a small number of groups with size equal to M basis functions, thereby casting the moment matrix into a collection of sub-matrices representing self-interaction and mutual interaction between the groups. Note that M is much smaller than N. Then, the procedure involves eliminating the interaction of two immediate neighbors in any selected group by generating a set of linear equations of size $2M \times 2M$ and solving using a standard linear equation solver. This process results in a diagonally dominant moment matrix, assuming the group size is sufficiently large. It also sets the matrix blocks residing on either side of the diagonal block to zero. Although the new matrix equation can be solved efficiently in many ways, it is solved very efficiently using a power series approach.[3]

The new approach is simple, efficient, and highly amenable to parallel processing while retaining all the advantages of the conventional MOM algorithm. The storage required for this new algorithm is 3N*M as opposed to N^2 for conventional MOM ($M<<N$). Parallel processing reduces the computation time drastically and near linear efficiency is achieved as more processors are used. With serial processing, the solution time varies as N^2, versus N^3 with conventional MOM.

Numerical Results: In this section we present results for the RCS of several objects. Figure 1 shows the azimuthal monostatic RCS at 10 GHz of the NASA Almond, shown in the inset of Fig. 1. The NASA Almond is a standard canonical shape that is difficult to model and is frequently used as a benchmark to test the accuracy of algorithms. The total surface area of the object is ~150 square wavelengths. The electric field is polarized along the z-axis. The object is approximated with 46,680 basis functions. For the new method,

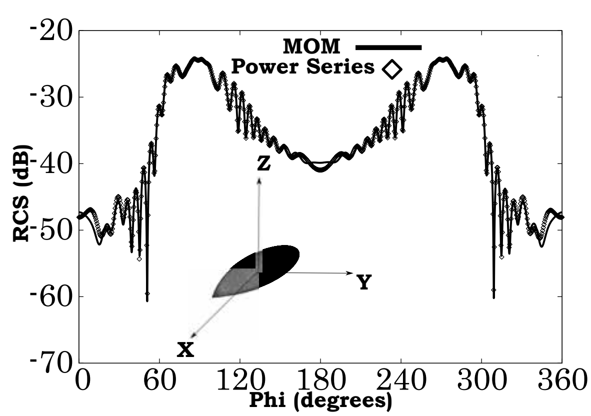

FIGURE 1
Monostatic RCS of the NASA Almond.

the total number of basis functions is divided into 20 groups with 2334 basis functions in each group. As is evident from the figure, the new method compares very well with the conventional MOM solution.

Figure 2 describes an aircraft-like model object illuminated by a 30 GHz signal with the electric field polarized along the x-axis traveling along the z-axis. The aircraft is located in the XY-plane with the nose along the x-axis. The total surface area of this object is around 100 square wavelengths. The aircraft is approximated by 25,080 basis functions. For the power series solution, the total number of basis functions is divided into 12 groups with 2090 basis functions in each group. The bistatic RCS along the XZ-plane is also shown in Fig. 2.

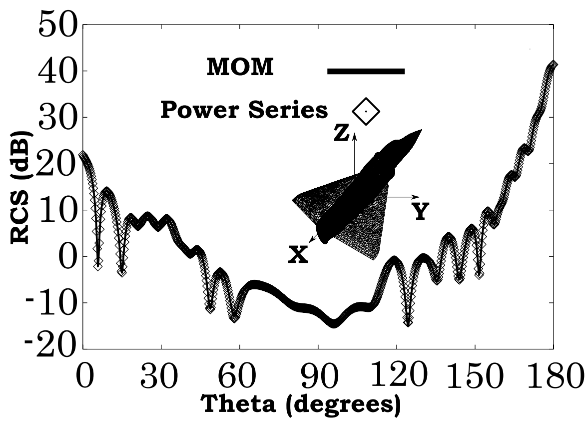

FIGURE 2
Bistatic RCS of an aircraft-like object.

Next, we consider a ship-like object, as shown in Fig. 3, illuminated by a 50 GHz signal. The surface area of this object is approximately 3000 square wavelengths at this frequency. The incident wave is y-polarized and traveling along the z-axis. The ship-like object is approximated by 864,800 basis functions. For the power series solution, the total number of basis functions is divided into 400 groups with 2162 basis functions in each group. The bistatic RCS along YZ-plane is also shown in Fig. 3. Note that no comparative solution is readily available because of the size of this problem. Finally, we note that although the results presented in this example involve N on the order of 1,000,000, it is possible to solve much larger problems with even more unknowns. The algorithm never directly uses N but only requires handling M unknowns, with M<<N. The new algorithm currently is the only option for the accurate solution of very large problems.

Conclusions: In this work, we present a new and efficient algorithm to predict the RCS of complex Navy objects at millimeter-wave frequencies. The method is very efficient, easily amenable to parallel processing,

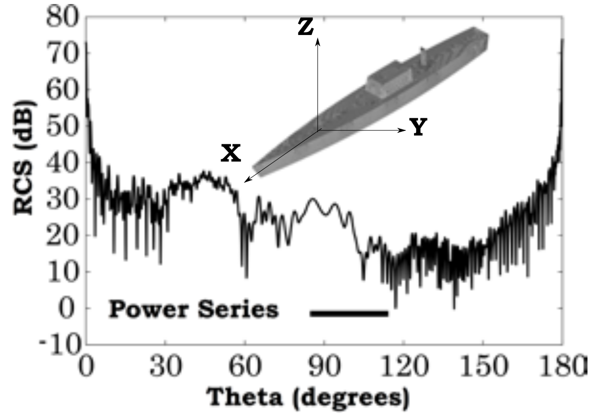

FIGURE 3
Bistatic RCS of a ship-like object.

and retains all the advantages of conventional MOM popular at low frequencies.

[Sponsored by the NRL Base Program (CNR funded)]

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Enabling Electronic Warfare Battle Management

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Introduction: The Office of Naval Research (ONR) and the U.S. Naval Research Laboratory's (NRL) Tactical Electronic Warfare Division have been pursuing significant and groundbreaking research on networked electronic warfare (EW) for the defense of the Navy's surface ships. This work started in 2009 with funding from the ONR SwampWorks high risk/high reward portfolio. As the technical challenges with networking EW systems using fleet tactical data links were understood, the technology migrated to ONR's Future Naval Capability programs and the Chief of Naval Operations Speed to Fleet portfolio. The successful development of this technology is driven by a process that includes an aggressive laboratory development schedule with regular at-sea experiments. These at-sea experiments are a critical part of the development process and hugely beneficial to the technology and to the NRL workforce. The development teams have spent 250 personnel-days at sea in the Pacific, Atlantic, and Mediterranean.

Networked Electronic Warfare: The terminal defense of a ship against a modern anti-ship cruise missile (ASCM) typically occurs in the last 120 seconds of the engagement. Worldwide there have been more than 200 ASCM engagements in anger since the 1967 sinking of the Israeli destroyer INS *Eilat*. ASCM defense is a difficult and fast-paced problem wherein the ship and crew are fighting for their lives. On a modern warship, there are over a dozen systems devoted to the defense of the ship. Many of these systems make heavy use of the electromagnetic spectrum. While defending a single ship is a difficult problem, defending a group of ships is even more difficult because the defensive actions of one ship may put other ships in the force at increased risk.

The canonical example of this occurred during the Falklands War in 1982 when British ships were attacked by Argentine aircraft launching Exocet (AM-39) anti-ship missiles. When HMS *Ambuscade* launched EW countermeasures, the missiles diverted and hit MV *Atlantic Conveyor* (Fig. 4) on the far side. MV *Atlantic Conveyor* was being used as an improvised aircraft carrier and amphibious assault ship, so with its sinking, the British lost seven of the campaign's eight troop transport helicopters. These types of interactions drive the need to coordinate and manage the electronic warfare response across the group of ships to ensure that the highest priority ships have the highest chance of survival.

In 2014 the Chief of Naval Operations articulated a broad vision on the critical nature of "Electromagnetic Maneuver Warfare" (EMW) for the Navy. The technical ability for the various and disparate EW systems to connect and function as a whole is an essential enabler for this EMW vision. The ONR and NRL research on the topic of networked EW systems anticipated this technical need years before senior Navy leadership articulated it.

The importance of testing at sea in the operational environment cannot be overstated as part of the technology development process that generates relevant and transitionable technology. As an example, during the TAPA EW experiment at the RIMPAC 2010 exercise, NRL scientists were working with their networked EW equipment on the midwatch (midnight to 6 a.m.) when a Navy early warning aircraft (an E-2C) joined the tactical network. To that point, the experiment had only been conducting only ship-to-ship coordination of EW assets. The NRL personnel immediately recognized the value of incorporating the E-2C's long-range and high-altitude sensor data into the experiment, and this was accomplished in real time. This serendipitous occurrence at sea led to several research initiatives in the following years (Fig. 5) to better integrate airborne assets into the surface navy tactical electronic warfare environment.

EWBM Architecture: As part of this effort, NRL has designed and implemented a novel software architecture to make it very easy for other programs to interact with the NRL-developed EW Battle Management (EWBM) backbone. The EWBM backbone can connect multiple shipboard EW systems together using a common EW language and software protocol. The EWBM backbone also spans multiple classification levels and takes advantage of multiple redundant communications links to join EW platforms together. The effectiveness of this technology at reducing the cost and integration time of these disparate systems resulted in the lead software engineer and system architect, Dan Robinson of NRL, receiving the 2015 Secretary of the Navy Innovation Award in the "Outside the Box" category.

FIGURE 4
The MV *Atlantic Conveyor,* used by the British in the Falklands War as an improvised aircraft carrier, was sunk when attacked by Argentine ASCMs. Other ships in the fleet launched EW countermeasures, diverting the missiles away from themselves.

FIGURE 5
NRL scientists perform a ground check of NRL-developed networked EW equipment with an E-2C of VAW-126 (Carrier Airborne Early Warning Squadron 126) in Norfolk, Virginia, in 2011.

sarily require a Navy EW program to change its own architecture to participate in the networked collection of EW systems. This element alone has already enabled the EW community to perform field demonstrations for tens of millions of dollars less, and in a fraction of the time, than if changes to each participating EW system had been required. The EWBM EW networking technology is completely government owned. This enables rapid (and low cost) adoption by multiple Navy laboratories and warfare centers.

Operational Impact: The EWBM software and architecture has already had a significant operational impact. The architecture is fielded on seven ships to support a CNO-directed urgent operational need. The

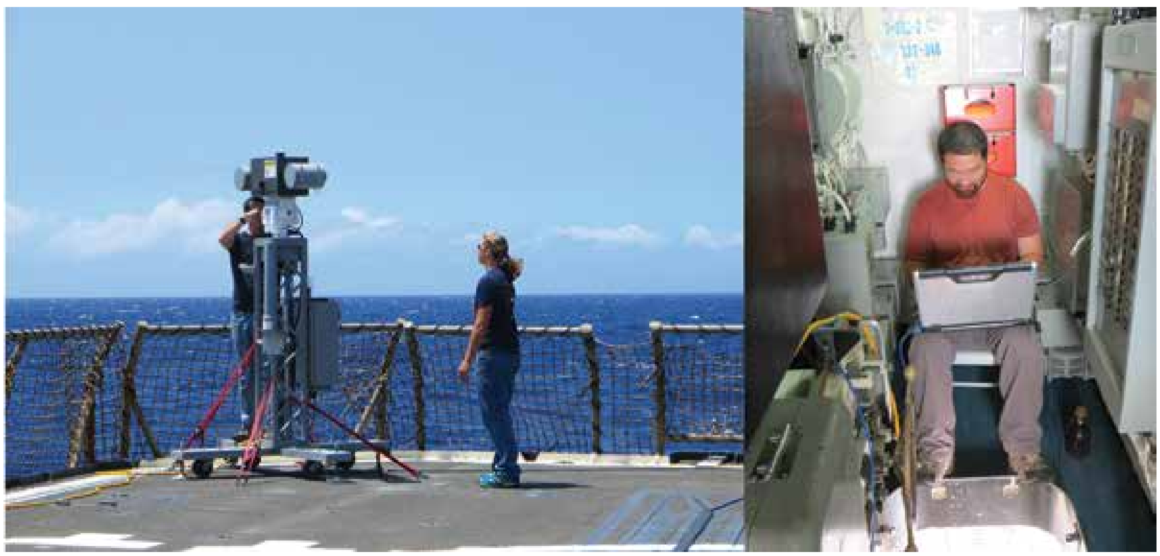

FIGURE 6
NRL scientists and EWBM equipment at sea as part of RIMPAC 2012.

The EWBM architecture developed by NRL is being used by all the major Navy laboratories (and one university laboratory) working on surface electronic warfare development. These organizations include NRL, Naval Surface Warfare Center Dahlgren, Naval Surface Warfare Center Crane, SPAWAR Systems Center Pacific, SPAWAR Systems Center Atlantic, and the Johns Hopkins University Applied Physics Laboratory. The EWBM architecture is also being used by Naval Air Warfare Center Point Mugu to interconnect aviation and Marine Corps EW systems with the surface Navy's EW systems. These interconnections between aviation EW and surface EW are both novel and powerful in the capabilities they bring to the combined arms fight.

The EWBM architecture enables developers working in different programming languages and on different computer architectures to pass fundamental EW data and EW intent between their systems. This is particularly important because it does not neces-

EWBM technology was also deployed on six ships from 2012 through 2015 in support of multi-ship and multi-system fleet EW experiments (Fig. 6). Getting real data at sea and building the Navy Research Enterprise's corporate experience at multi-ship and multi-system electronic warfare is important to provide a baseline from which new capabilities can be developed. These multi-ship and multi-system EW capabilities are required to defeat today's advanced anti-ship threats.

[Sponsored by ONR]

Radio Frequency All-Electronic Frequency-Selective Limiters

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Introduction: As co-site interference becomes ubiquitous and the threat of adversarial jamming expands, Navy systems must have the ability to adapt to and be protected from changes in a spectral environment. Tunable/switchable filters and limiters are important for this desired adaptability, but each has disadvantages. Typically, continuously tunable filters are difficult or resource-intensive to accurately control; switchable filters have significant switch loss; and most commercially available limiters provide high attenuation over wide bandwidths regardless of the bandwidth of above-threshold signals. At the U.S. Naval Research Laboratory (NRL), researchers in the Electronics Science and Technology Division (ESTD) are developing new types of channelized filters and multiplexers with frequency responses determined by digital control signals, input RF power levels in each channel, or both. When controlled by input power level, the new circuits behave as frequency-selective limiters that have the advantages of commercially available wideband limiters — i.e., high speed, tunable threshold, and ease of manufacture — without the disadvantages of previously demonstrated frequency-selective limiters based on ferrite materials — i.e., small-signal insertion loss, low speed, and need for magnetic bias. These new circuits will enable future Navy systems to operate with high sensitivity while co-located with other high power RF systems.

Approach: By placing high-performance wideband limiter components at key locations in circuit architectures that are inherently frequency selective and designed to take advantage of the changing impedance of the wideband limiter components, frequency-selective limiters can be made with only electronic components. One example is a particular type of multiplexer that is advantageous for frequency-selective limiting due to its contiguous channels in both amplitude and phase, ability to limit in a particular channel without affecting adjacent channels, and channel filter topology that enables channel insertion loss to smoothly vary with input power using only passive components.[1] As the input power to the channel filters in this topology increases, the coupling between interior resonators decreases. This reduces signal transmission through the channel while maintaining approximately constant input impedance. A suspended stripline version of this multiplexer with integrated limiting and six 52.5 MHz bandwidth channels was designed for the 970 MHz to 1285 MHz band. A conceptual illustration of its operation is shown in Fig. 7(a), and pictures of the circuit are shown in Fig. 7(b). Limiting occurs only in channels that experience high power signals, allowing a receiver to operate with high sensitivity in other adjacent channels.

While the multiplexer topology described above enables frequency-selective limiting over moderate bandwidths, many Navy systems operate over much wider frequency ranges. To provide frequency-selective limiting over bandwidths greater than an octave, ESTD researchers created a bandstop filter architecture.[2] Each bandstop filter independently limits when it experiences high power and behaves as a transmission line outside of its bandwidth, allowing multiple filters to be placed in cascade. We recently designed a single-channel bandstop limiter and are now developing a 15-channel S-band frequency-selective limiter.

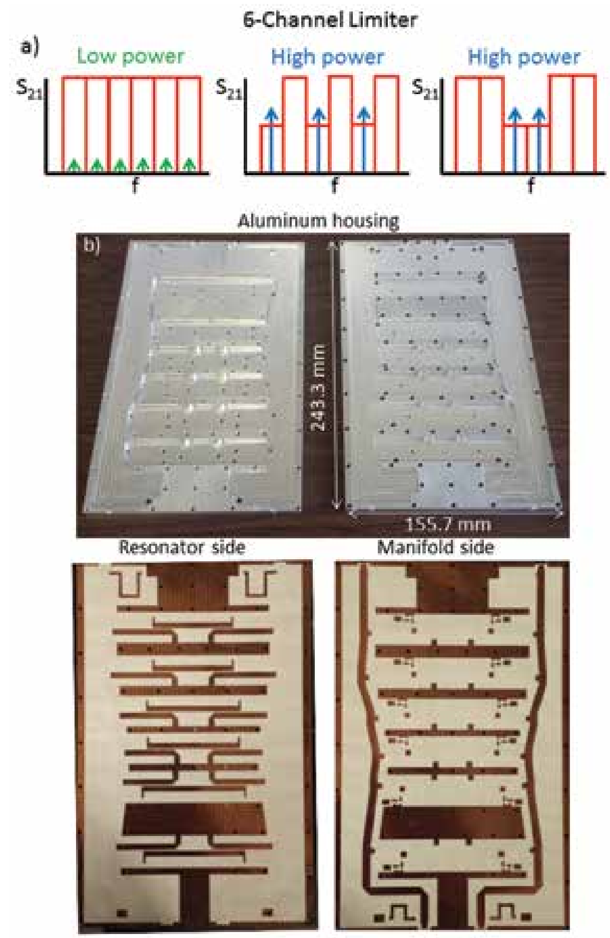

FIGURE 7
Six-channel limiting multiplexer. (a) Conceptual operation. (b) Photographs of fabricated prototype.

Results: Measured results of the six-channel limiting multiplexer described above are shown in Fig. 8. Figure 8(a) shows six states when the channels are actively switched with a digital control signal. Chan-

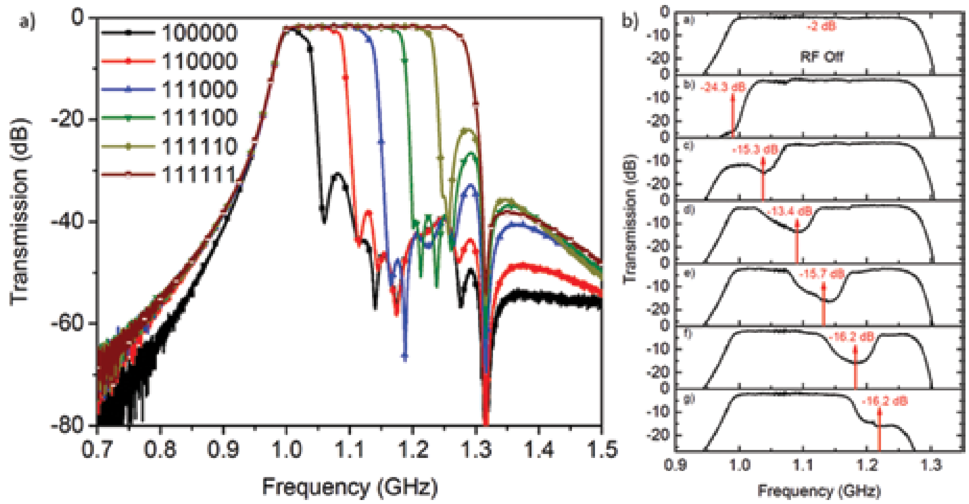

FIGURE 8
Measured responses of six-channel limiting multiplexer. (a) Operation in digitally switched mode. (b) Operation in power-limiting mode, where an attenuation band appears around any high power signals.

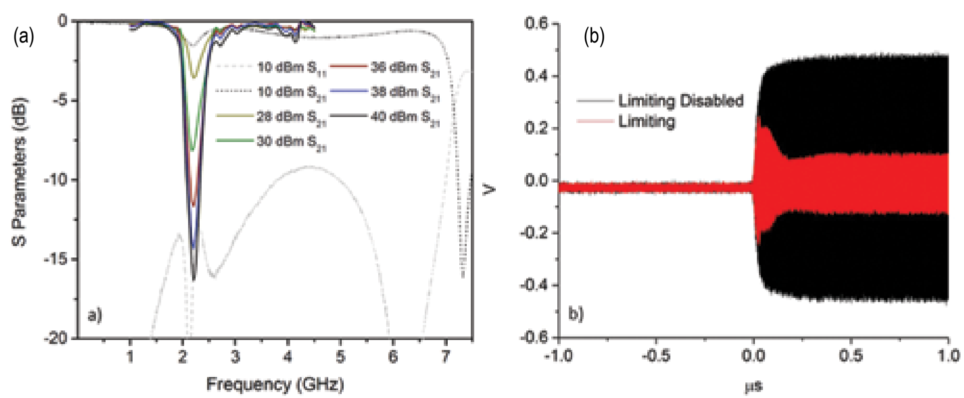

FIGURE 9
Measured responses of bandstop limiter. (a) Attenuation increases in band as input power increases. (b) Time domain measurement of leading edge of high power pulse.

nels are switched into the response from low to high frequency, where “1” represents an on channel and “0” represents an off channel. In this mode, the multiplexer can be operated as a reconfigurable filter, and it has a total of $2^6 = 64$ states. Figure 8(b) shows measured results when a 5 watt tone, denoted by a red vertical arrow in the figure, is swept throughout the passband. An attenuation band automatically follows the tone, and no control signals are needed in this mode. The multiplexer provides limiting selectively in only the bands that are experiencing high power. In addition, the limiting threshold is tunable from 15 dBm to 35 dBm.

Measured results of the single-channel limiting bandstop filter are shown in Fig. 9. Figure 9(a) shows the transmission response as input power is increased. From 25 dBm to 40 dBm, attenuation increases from 1.6 to 16.5 dB in only the narrow band of the filter. Figure 9(b) shows time domain measurements of the leading edge of a 5 watt pulse sent through the limiting bandstop filter. The limiting filter is fast enough to never allow the full power of the pulse through the device when limiting is enabled. Several of these limiters that cover successive frequency bands will be cascaded in order to provide multiband frequency-selective limiting over a wide bandwidth in a future design. This circuit will allow very wideband Navy receivers to operate with high sensitivity in the presence of co-site and adversarial jammers.

[This material is based upon work supported by ONR (N0001417WX00109) and DARPA. The views, opinions, and/or findings contained in this article are those of the author(s) and do not necessarily reflect the views of ONR, DoD, or the U.S. Government.]

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Microwave Noise Characterization of Active Devices

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Introduction: Transistors are at the core of any modern electronic systems. The recent "wireless revolution" has enabled point-to-point, two-way instantaneous interactions and it is pushing the transistor technology toward higher and higher frequencies to support wider bandwidths and faster speeds. Similar trends are unfolding for military applications such as radar and communications systems.

The detection of an incoming signal is ultimately constrained by the noise of the receiving system. Active devices must be sensitive enough to detect weak signals and process the information they carry. Indeed, enhancing a system's dynamic range by improving its sensitivity rather than increasing its radiated power often translates to less expensive, smaller, lighter component requirements with reduced prime power demand.

The goal of any receiver is to avoid degrading the incoming signal to a point that it can no longer be processed and detected. The fundamental limit is set by the random noise processes inherent to any electronic component. Understanding and quantifying the noise performance of an active device is key to designing new sophisticated electronic capabilities.

Noise Parameters: The noise performance of a microwave system is generally quantified by its noise figure. The noise figure describes the degradation of the signal-to-noise ratio between the system's input and output ports. The noise figure information is not sufficient to design electronic circuits. This is because at the circuit level, the transistor's noise performance is dependent on the impedance level at which the transistor's input nodes are driven. Indeed, it can be proven experimentally and theoretically that, for a given bias and at a given frequency, a minimum degradation is experienced by the incoming signal when the transistor is driven by an optimum impedance value of the source. Any variation from this optimum value worsens the transistor's noise figure and degrades the system's sensitivity.

The quantities that capture the noise performance of an active device for a given bias point and frequency are known as the transistor's noise parameters and are often indicated by semiconductor manufacturers as minimum noise figure, F_{min}, optimum source reflection coefficient, Γ_{Sopt}, and equivalent noise resistance, R_n. The noise figure associated with the active device for any source impedance values can be computed from the noise parameters. A graphical visualization of the noise figure as a function of the source impedance is shown in Fig. 10. The steepness of the cone's surface is associated with R_n. Providing the circuit designer with a model of the active device that includes the noise parameters is key to enable first-pass designs.

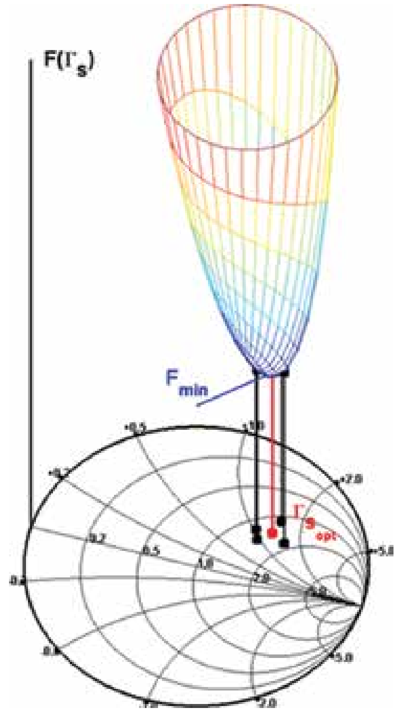

FIGURE 10
Visualization of the noise parameters.

Noise Parameter Characterization: The determination of the noise parameters at microwave frequencies is well known.[1] The basic idea is to make noise figure measurements as a function of the source impedance and then fit the measured data to obtain the noise parameters that best approximate the cone of Fig. 10. The procedure requires the generation of a number of source impedance values. The microwave component that meets this need is a microwave tuner. Figure 11 shows a typical set of commercially available tuners used in modern test and evaluation laboratories. A tuner's size depends on the frequency range at which it operates: the lower the frequency, the bulkier the tuner. Tuner operation may be controlled by a computer to enhance the repeatability of the measurement. In general, this type of noise parameter measurement setup is cumbersome.

A novel and unique technique that removes the requirement of an external tuner has been devised at the U.S. Naval Research Laboratory (NRL). The greatly simplified measurement setup allows noise characterization of devices operating at millimeter-wave frequencies and it is specifically tailored to on-wafer transistors.

FIGURE 11
Typical noise parameter measurement setup with microwave tuners.

NRL's new technique relies on the experimental fact that the signal and noise behavior of a transistor scale with its size when the device is biased at constant current density. Hence, it is possible to make noise figure measurements as a function of device size rather than as a function of the input impedance. An appropriate analytical framework has been developed to seek a best-fit of the data against a known function to determine the noise parameters. The function is defined by a well-known noise model for microwave devices.[2] It should be noted that semiconductor manufacturers routinely produce devices of different sizes and this is not a constraint on the applicability of NRL's new technique.

NRL demonstrated the new method with measurements of six gallium nitride (GaN) high-electron-mobility transistor (HEMT) devices, each of known size.[3] The measurement ranged from 2 to 15 GHz for the demonstration. The signal model was validated from scattering parameter measurements before using it against noise figure data as shown in Fig. 12. The excellent results demonstrate the validity of NRL's new technique.

Summary: A new analytical method of determining the noise parameters of a transistor has been developed and validated experimentally at NRL. A patent has been awarded by the United States Patent and Trademark Office.[4] The new technique drastically reduces measurement complexity and improves measurement speed. The new method is a unique capability available at NRL to support first-pass designs of high-frequency, low-noise circuits to enhance the sensitivity of new electronic systems.

[Sponsored by the NRL Base Program (CNR funded)]

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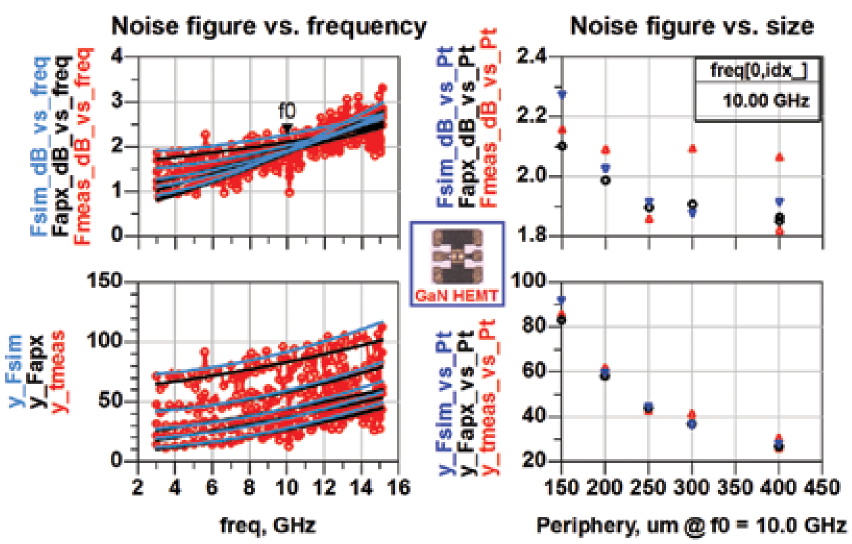

FIGURE 12
Model vs measurement comparison of device noise performance (blue = simulated; black = approximated; red = measured).

Information Technology and Communications

NRL SCIENCE AS ART CONTEST

Laboratories for Computational Physics and Fluid Dynamics Choice

Tale of Coherent Structures in Asymmetric Supersonic Jet Flow (.mp4)

The takeoff and landing noise of powerful advanced military jet aircraft impacts the health and safety of flight line workers. To confront the challenges of the noise problem, NRL researchers in the Labs for Computational Physics and Fluid Dynamics study simulations of the flow from the rectangular nozzle exhaust of a supersonic jet engine. Rectangular nozzles offer attractive features like better airframe integration, fewer parts, and potentially better noise reduction through its design and setup. NRL researchers observe increased stretching and mixing of flow eddies, shown as isosurfaces of vorticity and Q-criterion, at the corners, resulting in an asymmetric jet much different from the symmetric jet of a circular nozzle. They seek to leverage this asymmetry and use it to affect the direction in which most of the noise is radiated, thus potentially creating quiet zones for human operation.

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Age of Information Under Random Updates

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Introduction: Timeliness of information delivery is a crucial requirement in tactical communications, particularly for information updating applications, such as blue-force tracking, RF spectrum monitoring, and proactive routing protocols. We are interested in understanding the performance of real-time information updating applications that are deployed in a network setting, as depicted in Fig. 1. In this system, the source transmits periodic messages to a monitor, to convey the most recent state of some information source. Traditionally, network performance has been measured using common metrics such as *delay* and *throughput*. However, neither delay nor throughput is adequate for characterizing the freshness of information as observed at a monitor. Therefore, when optimizing the performance of these applications, it is important to define a metric that accurately describes the objective of such systems.

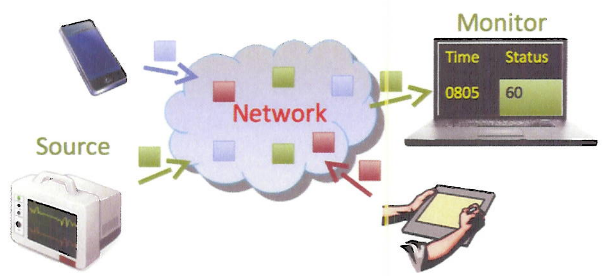

FIGURE 1
Real-time information updating system (green) with competing network traffic (blue/red).

We study a new metric called the *status age*, or the *age of information*, which specifically characterizes the performance of such information updating applications. The age metric is defined as the duration between the time of observation at the monitor and the time at which the observation was generated at the source.[1] Prior studies on the age metric analyzed the performance for a single server queue, but this does not sufficiently model the dynamics typical of tactical networks. In this work, we analyze the age metric for an infinite server queue, which models certain aspects of dynamic networks such as packets arriving out of order at a monitor, while also enabling tractable mathematical analysis. Our analysis and numerical results illustrate the trade-off between the freshness of information and resource utilization.

System Model and Analysis: We study a system in which a source transmits packets through a network to a remote monitor, which we model as an infinite server queue. Since there is an infinite number of servers, a packet does not wait in a queue but immediately enters a server. The packet completes service after a random time, which represents the time it takes for a transmitted packet to traverse the network and arrive at the monitor. Since packets immediately begin service and their service time is random, there are many possibilities for the order in which packets arrive at the monitor. For instance, a packet may arrive at a monitor after another packet that was transmitted more recently (and contains fresher data), in which case we say that the later arriving packet is obsolete since it contains old data.

Figure 2 is a sample plot of the age as a function of time, where the t_i represents the transmission instant for packet *i*, and τ_i represents the instant packet *i* is received at the monitor. In this example, packet 3 arrives at the monitor after packet 4, and is thus considered obsolete. Motivated by this graphical representation of the age, we mathematically compute the average age (i.e., the expected age of information observed at the monitor) for some random models of the packet generation and service processes.[2,3] By accounting for all possible events of the order of packet arrivals, we derive a mathematical expression of the average age. In addition, we derive the probability that an arriving packet is not obsolete. The percentage of obsolete packets can be interpreted as a waste of network resources, since these packets do not provide fresher data but still occupy the network before arriving at the monitor.

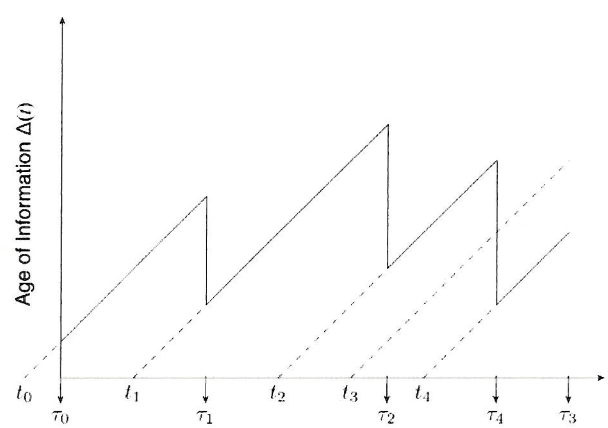

FIGURE 2
Time evolution of the age of information metric.

Results: After computing the mathematical expressions for the average age and the probability of a packet being obsolete, we numerically evaluate them and present the results in Fig. 3.[2,3] The average age Δ is plotted as a function of utilization ρ (the generation rate divided by the service rate μ) for various values of the service rate μ. The first key observation is that with an increasing generation rate (or utilization), the average age is strictly decreasing. This differs from the single server case, in which the age initially decreases to a minimum (optimum age) but then increases again as packets grow stale while waiting in the queue. For the model considered in this work, the age is minimized as the generation rate goes to infinity, since there are infinite servers, and more frequent transmissions leads to more frequent updates at the monitor. The second key point is that the increase in generation rate comes at the cost of needless consumption of network resources. The percentage of obsolete packets (green dotted line, right-hand y-axis) increases with utilization, and they do not provide fresh information and are ultimately wasting resources.

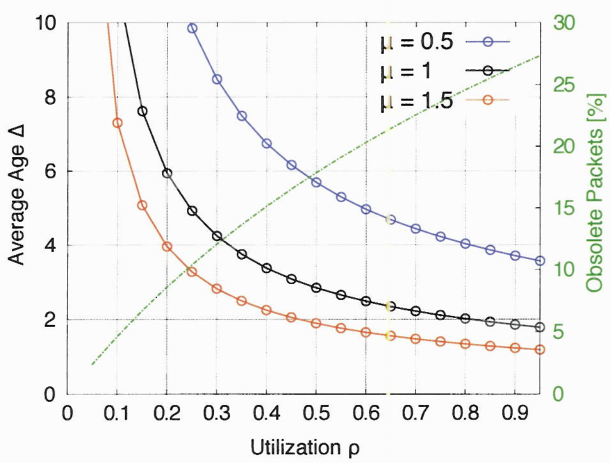

FIGURE 3
Average age (for various μ) and % obsolete packets vs utilization.

Summary: We have evaluated the performance of information updating applications deployed in a dynamic network, using a new metric known as the age of information. We show that, on average, the monitor sees the freshest information if we increase the rate of packet generation, but at the cost of wasted network resources. Understanding the age metric will improve the performance of numerous tactical networking applications and quantify the impact on the efficiency of resource utilization.

[Sponsored by the NRL Base Program (CNR funded)]

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Behavioral Web Analytics

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Introduction: This U.S. Naval Research Laboratory (NRL) work leverages the voluminous quantity of digital traces generated by web browsing activities to construct a cognitive fingerprint for either authentication purposes (in conjunction with other biometric techniques) or for finding persons of interest. We describe the features of web browsing behavior across web sites from a metadata point of view (that is, without access to the content of the web page visited), and the machine learning methods for authentication. We generalize this approach to data obtained from a social media site, Reddit, and describe current work on composite identities. This work has application to insider threat identification in detecting and characterizing change of behavior at an individual level rather than at an aggregate level. It also has application to recommender systems in the automatic construction of user profiles, removing the reliance on possibly deceptive user-created profiles.

Technical Approach: We conducted user studies to obtain our clickstream data using browser extensions developed as part of this research to record timestamps and URLs as they appear in the address bar of the browser. The clickstream data was then segmented into sessions: that is, a continuous stream of pageviews delimited by pauses of 30 minutes or greater. The features of web browsing behavior can be grouped as follows: (1) global session features such as day-of-week, time-of-day, number of pageviews, and average pageview duration; (2) time-variant features to capture temporal characteristics of pageviews within a session, such as pauses defined as the elapsed time between clicks, bursts defined as the change in pause time between clicks or second order pauses, and pageview revisits whereby some web pages act like commonly used words in a sentence; and (3) semantic session features based on encoding web pages into genres. Genres are functional categories of information presentation; in other words, genres are a mixture of style, form, and content. We claim that genres are more indicative of user behavior than topics are. For example, students read tutorials regardless of subject matter. We initially leveraged a web service, http://www.diffbot.com, to classify web pages into genres but developed our own custom genre classifier when the service was no longer freely available. Our genre classifier is based on URLs only[1] and our genres are tailored to URL mnemonics reflecting expectations (i.e., "mail," "forum," "wiki," etc.). What most surprised us in the analysis of the clickstream data was the unexpected ways the power law of human activity, $f(x) = ax^{-k}$, manifested itself through the features (Figs. 4 and 5). Not only do the time-variant features obey the power law, but so do the frequencies of the genres of the web pages.

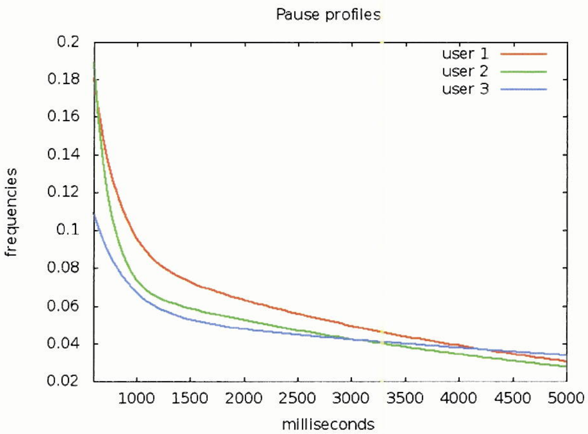

FIGURE 4
Pause profiles for three users for pauses less than 5 seconds.

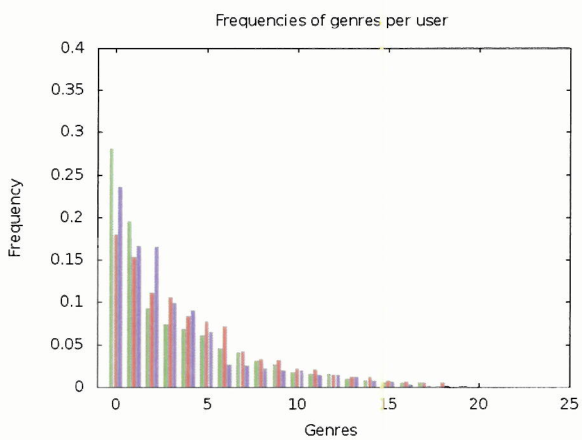

FIGURE 5
Genre frequencies for three users.

The next step of our research consisted of automatically constructing user profiles with the underlying assumption that persons of interest could be found by similarity to a prototype profile. To evaluate techniques for constructing a user profile, we turned to machine learning techniques for authentication, and biometrics for evaluation of the false rejection rate and false acceptance rate. We came up with two approaches. The first is an ensemble approach of one-class *support vector machines* using a random subspace approach.[2] Our ensemble approach trains a pool of learners from randomly generated subsets of the features (it is worth noting that none of the features by themselves were good authenticators). The second is a temporal approach using *conditional random fields* decomposing the clickstream data into overlapping n-grams of clicks.[3] Our conditional random fields approach combines different neural network architectures with the Viterbi algorithm to obtain a score for the "best" sequence of genres. A threshold is then obtained to discriminate between self and non-self. Several summer students working in the Information Technology Division at NRL tried different machine learning techniques for authentication from social media datasets such as Reddit and Twitter. Social media have a way to crowdsource the tagging of content by its users and therefore have minimal noise in capturing semantic features. One interesting student project involved inferring the personality of Reddit users by their similarity (through clustering of visited topic-oriented forums called subreddits) to users frequenting one of the 16 Myers-Briggs subreddits.

We are now extending our work to address the composite identity problem (one-to-many) wherein multiple users hide behind one identity, either intentionally (e.g., moderators, group operatives, original user abandonment of device, compromised account) or unintentionally (e.g., sharing a computer in a household or public library). The approach has to determine, without prior information, whether an account is populated by a single user or by multiple users. Our technical approach is based on subspace clustering whereby feature selection combines with cluster formation in training different models iteratively using the Expectation-Maximization algorithm.

Summary: The main contribution of this work is the automatic construction of user profiles from digital traces. We found that a temporal approach, albeit more computationally intensive, gives us a more accurate model than a feature vector approach aggregating data by sessions to identify behavior. The n-gram approach enables us to detect frequent sub-sequences specific to a user. Accurately and efficiently encoding the type of web page remains a challenge. This work has touched on many areas of research in representing and learning models of human behavior and computer interaction.

Acknowledgments: We thank our volunteers and enthusiastic summer students.

[Sponsored by the NRL Base Program (CNR funded)]

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A Novel Software-Defined Radio Relay

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Overview: Beyond-line-of-sight (BLOS) communications requirements can be met by using airborne radio relays. In the past, analog radio signals could be easily relayed with simple, inexpensive devices on airborne platforms. The advent of digital communications enabled more sophisticated modulation techniques and communications architectures. While providing better communications performance, these techniques require more complex and expensive relays.

Modern relays fall under two separate categories: queuing relays and memoryless relays. The work described here extends upon low-power memoryless relays that do not have the ability to queue packets and are simpler to implement than queuing relays. Memoryless relays fall into the following subgroups:[1]

Amplify-and-Forward (AF) relay boosts the received signal and transmits the boosted signal to the channel in the next timestep. The AF method requires significantly less computing power for modern waveforms, as no decoding operations are performed on the relay.

Compress-and-Forward (CF) relay compresses the received message signal in one block and transmits the compressed message signal to the channel in the next block timestep.

Decode-and-Forward (DF) relay decodes the received signal to a bitstream block, corrects for bit errors in the block, encodes the corrected bitstream block to an encoded signal, and transmits this encoded signal to the channel in the next block timestep.

Relaying techniques based on software-defined radios can be employed that achieve power savings compared to conventional digital DF relays. The software-defined radio (SDR) relay approach allows the relays to rapidly adapt to the RF environment and dynamically switch between three relaying methods. This optimizes the performance of the relays for the channel while minimizing power consumption. In the Voice Systems Section of the U.S. Naval Research Laboratory's Information Technology Division, these relaying approaches were designed and demonstrated using MATLAB/Simulink and an SDR platform connected to military VHF radios. The final results show that a group of software-defined radio relays will outperform a group of conventional digital DF relays without increasing outage.

Implementation and Results: The software-defined radio relay was implemented with three separate data paths. Path 1, the AF relay, consists of the SDR receiver connected to the multiport switch, which is connected to the SDR transmitter. Path 2, the CF relay, consists of the AF relay components, the FM demodulator subsystem, and the FM modulator subsystem. Based on Carson's bandwidth rule, $CBR = 2(\Delta f + f_m)$, the CF relay modifies the message bandwidth (f_m) to reduce the transmitted bandwidth (CBR). The peak frequency deviation (Δf) stays constant. Path 3, the DF relay, consists of the AF relay components, the FM demodulator subsystem, the FM modulator subsystem, and continuously variable slope delta modulation (CVSD) decoder and encoder subsystems. CVSD was chosen because it is the least complex DF method for voice communications and has acceptable noise immunity. The SDR relay data path is illustrated by the model in Fig. 6.

The control logic for the multiport switch must be carefully designed to enable power savings for ideal RF channel conditions while operating in less than ideal conditions. Measurable RF parameters that indicate the relay is operating in less than ideal conditions include adjacent channel interference and low signal-to-noise ratio. Additionally, if mission duration is a priority, then battery life should be monitored as well. The overall approach is to periodically measure multiple RF parameters in the military environment and use these measurements to dynamically choose the optimal relay approach for a particular RF channel. Below are the steps in determining when to switch between modes:

- Measure adjacent RF channel interference to determine if CF relay method should be selected.
- Measure signal-to-noise ratio to determine if DF relay method should be selected.
- If applicable, measure remaining battery life with respect to mission duration to determine if AF relay method should be selected.

The DF method was determined to be the least power efficient method after comparing computational time on the fixed models. The ratios of computation time were used to estimate current draw of 0.6, 0.8, and 1.5 amps for the different modes. An existing analog AF relay provided a baseline of 0.6 amps current draw.[2] Battery voltage was set at 15 volts. Next, groups of relays operating in the following four different relay modes were modeled to compute total power consumption: AF mode, CF mode, DF mode, and SDR relay

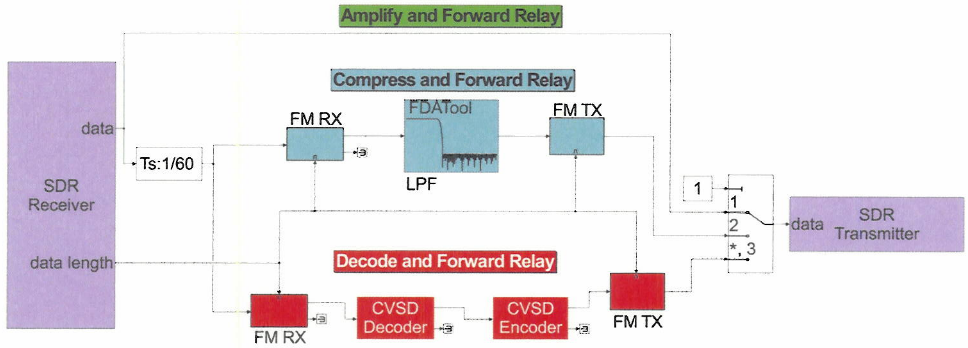

FIGURE 6

The separate data paths in the proposed software-defined relay are illustrated in a MATLAB/Simulink model followed by a multiport switch prior to the transmitter block. Amplify and forward is on top for path 1. Compress and forward is in the center for path 2. Decode and forward is on the bottom for path 3. The control logic is not illustrated. (Ts = time to sample a frame; FDATool = MATLAB/Simulink filter design and analysis tool; LPF = low pass filter.)

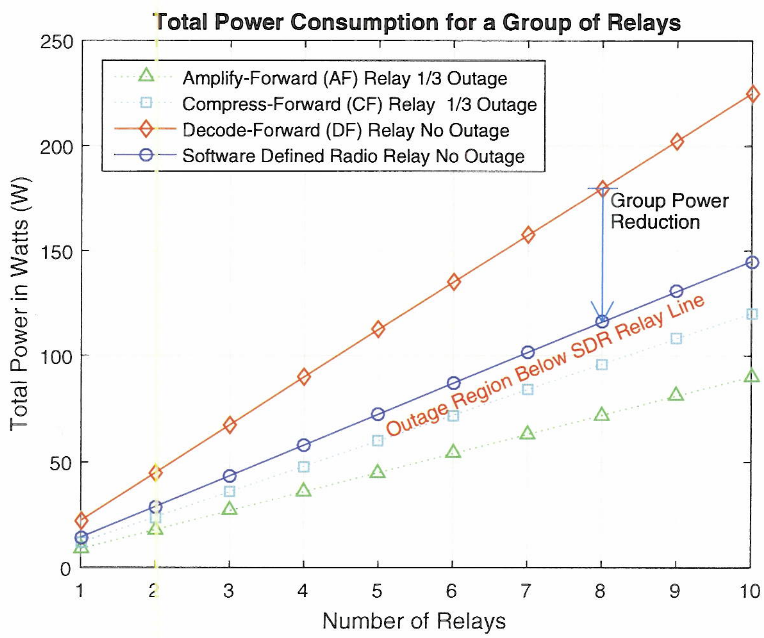

FIGURE 7

Estimated group power (lower is better) reduction over decode and forward relaying for a software-defined radio relay group that achieves 0 outage during low SNR. Probabilities of 1/3 were used to determine if the SDR relay was operating in AF, CF, or DF mode. Additionally, the current draw was estimated at 0.6, 0.8, and 1.5 amps for the respective modes with a supply voltage of 15 volts. Current draw of 0.6 amps for AF mode was estimated from prior work on the Surrogate TACSAT AF relay.[2] Although both AF and CF modes achieve lower total group power consumption compared to the SDR relay, both methods have outage 1/3 of the time due to their inability to relay for low SNR channels.

mode. For the SDR relay mode, probability of low SNR was 33.3%, adjacent channel interference was 33.3%, and the remaining 33.3% was operating in AF mode. Figure 7 illustrates that the SDR relay achieves power savings over DF mode without outage. Both CF and AF modes encounter increased outage during low SNR.

Conclusion: When compared to traditional DF relays, advantages of the proposed software-defined radio relay include lower power consumption, longer mission duration when operating from battery power, and ability to adapt to observed adjacent channel interference through bandwidth compression. When compared to traditional AF relays, advantages of the SDR relay include no outage under low SNR and the ability to reduce adjacent channel interference during conditions of congested RF spectrum. When compared to traditional CF relays, advantages of the SDR relay include no outage under low SNR.

[Sponsored by the NRL Base Program (CNR funded)]

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Translating Observational Techniques from Law Enforcement to Peacekeepers

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Information Technology Division

Introduction: Translating research into operation is an important mission. In 2015, the Adversarial Modeling and Exploitation (AMX) Office at the U.S. Naval Research Laboratory (NRL) designed and developed the Identifying Threats in Peacekeeping Environments course to increase skills related to identifying deception and the concealment of contraband. This training course is the culmination of a multiyear project called Just Doesn't Look Right (JDLR). This article describes the steps taken, progress made, and lessons learned from this experience making research practical.

The JDLR Project: The focus of the JDLR project was to characterize the cues used by law enforcement for interdiction in terms of observable behaviors. As a starting point, cues and their contexts were drawn from the criminal justice literature and interviews with law enforcement personnel. Focus groups of experienced practitioners from local, state, and federal law enforcement articulated the behaviors they use to identify persons of interest. In Phase I, we concentrated on detailing specific observable behaviors that indicate a subject is carrying contraband — either an illegal handgun or narcotics. In Phase II, we conducted a series of workshops to explore how observable behaviors impact decision making by law enforcement during an interaction with a person of interest. For the transition phase, Phase III, we conducted a site visit to the National School of Peacekeeping Operations of Uruguay (ENOPU) and held a series of focus groups to understand the needs of Uruguayan peacekeepers to execute their assigned Global Peace Operations Initiative (GPOI) mission in the Democratic Republic of the Congo (DRC) (Fig. 8).

FIGURE 8
Peacekeeping in the Congo.

A Course for Peacekeepers: Following the site visit to ENOPU, it was clear that the best means of fulfilling the GPOI mission to train and sustain peacekeeping proficiencies was to create a course on identifying threats based on our observational behavior research. The AMX team designed and developed an instructor-led train-the-trainer course using instructional design principles and best practices in adult learning including classroom instruction, role-playing activities, and reality-based training (RBT). The focus of the course is on protection of civilians and peacekeepers; Fig. 9 shows the course modules. The ENOPU delivery is tailored for platoon leaders and senior noncommissioned officers as a supplement to their predeployment training. All materials were translated into Spanish and the course is instructed in English and Spanish.

Transition: Efforts to transition the course are ongoing. This transition involves gradually incorporating Uruguayan personnel into the course of instruction,

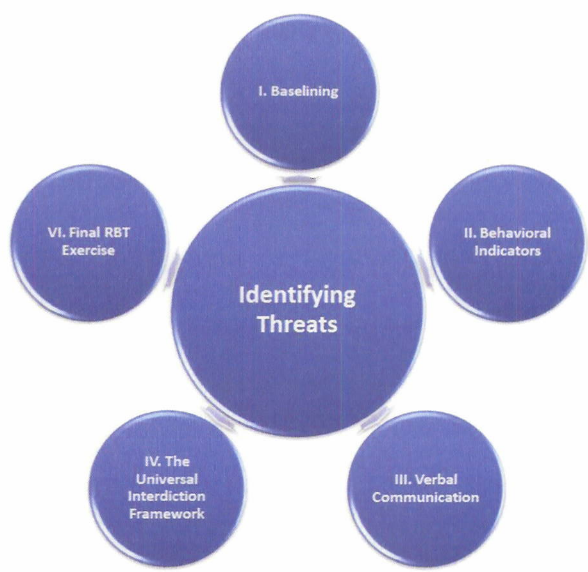

FIGURE 9
Course modules.

first as coaches, then co-teaching the course with AMX instructors, and then operating as full instructors. To date, the AMX team has delivered the course three times and trained two Uruguayan instructors, seven Uruguayan coaches, and 65 platoon commanders/enlisted personnel. Many of these trainees are currently deployed on peacekeeping missions.

Lessons Learned, Research to Operation: A number of important lessons were learned taking the JDLR project from a research project to an operational program. First, a sustained commitment to business development is critical. This process took time and significant lobbying at the domestic and international level by the project principal investigator, sponsors, and partners. Second, investing the time to understand our transition partner's operational environment enhanced the sustainability of our project. Our training course needed to be framed in a way that would resonate with the target audience's mission requirement. Our ability to engage the students was enhanced when we began co-teaching the course with Uruguayan coaches and instructors we had trained previously. Third, we benefitted from collecting readiness assessments, daily critiques, and exit assessments. These data allowed us to gauge receptivity, identify areas in need of improvement, assess the potential benefits of our course, and provide data to our sponsor, facilitating ongoing support. Fourth, we learned to be flexible and to cultivate a variety of funding streams to sustain the project. Research results are applicable to a variety of environments and it is often our responsibility to make those connections. Finally, establishing and maintaining a partnership with our ENOPU partners and the support personnel (both foreign and domestic) allowed us to successfully execute course deliveries and address problems before they became unsurmountable.

Future Work: The process of translating research into practice has been a challenging but rewarding experience. Like many of our research endeavors at NRL, there is always a desire to expand our research and ask new questions. Our next steps include working with the Global Peace Operations Initiative Program at the United States Southern Command (USSOUTHCOM) and the Uruguayans to transfer relevant knowledge, tools, and techniques to an entire platoon of enlisted personnel and to assess the impact of this course on the mission in the DRC. We will also continue to assist our Uruguayan partners as they instruct their own personnel and to work with them as they expand course delivery to other partner nations throughout South America and beyond. In addition, we are developing a modified version of the course for use in the United States that focuses on fair and impartial policing, to assist the officers and organizations that contributed to the JDLR project.

Acknowledgments: This research and development endeavor would not have been possible without the support of the Office of the Secretary of Defense (Acquisition, Technology and Logistics) Rapid Reaction Technology Office and the Global Peace Operations Initiative Program at the United States Southern Command (SCJ54/GPOI).

[Sponsored by USSOUTHCOM GPOI]

Blind Adaptive Communications Network Layer Inference

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Introduction: Traditional communications networks use established standards and specific allocated frequency spectrum to communicate, so the physical layer transmission (PHY) parameters are directly associated with the network type and protocols. Meanwhile, adaptive communications networks share the same spectrum by sensing and adapting their PHY parameters such as channel, bandwidth, and modulation to avoid interference, so there is no longer a direct correlation between these parameters and the type of the adaptive network. Here, we demonstrate the ability to blindly infer which emitters are in the same network, learn how they share the spectrum, and identify the

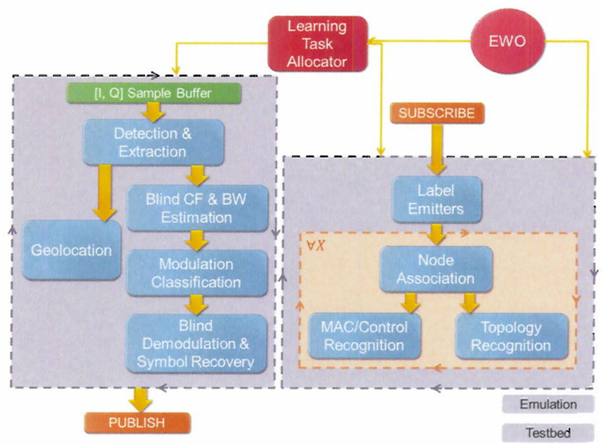

FIGURE 10
Blind physical layer characteristic extraction through blind network topology recovery. (CF = center frequency; BW = bandwidth; EWO = Electronic Warfare Officer.)

underlying network topology based only on observed patterns of communications (see right side of Fig. 10). This ability to learn the network layer protocols provides an increased level of situational awareness on communication networks of interest.

Methods: *Network Association.* The goal of network association is to discover which radios in the environment are communicating. Intuitively, nodes in the same network have a reciprocal relationship, so that packets transmitted from one radio result in packets being transmitted in another radio. That is, packet transmission times in communicating radios are causally related and not random. To model this relationship, we use a probabilistic model that tests if pairs of transmissions are random. The model is based on a multidimensional Hawkes process,[1–3] which is similar to a Poisson process, but with the conditional intensity function depending on previous transmissions.

Network Protocol Learning. Once the devices in the same network are identified, further situational awareness is provided by examining the network protocol used by those devices, including the medium access control (MAC) and control plane. The MAC controls how devices in the same network share the spectrum in time and frequency, and the control plane regulates network traffic.

Medium Access Control (MAC). MAC protocols regulate network access in either time or frequency, which is achieved by deterministic rules or randomized access. Common MAC protocols include time division multiple access (TDMA), carrier sensing multiple access (CSMA), and frequency division multiple access (FDMA).

MAC recognition is performed by analyzing whether devices communicate at different times, different frequencies, or both. First, all transmissions at the same center frequency (within some tolerance) are grouped. For each frequency, a histogram tracks the number of transmissions from each transmitter. If only one transmitter is using a particular frequency, then the MAC is likely FDMA. If multiple users transmit on that frequency, then the network is likely utilizing TDMA or CSMA. To further differentiate between TDMA and CSMA, the packet arrival times are analyzed. In TDMA, devices transmit in fixed, periodic time slots, while in CSMA, devices randomly transmit data by sensing the spectrum in a given frequency band and opportunistically using it when available. If the inter-packet arrival time histogram is periodic as measured by the absolute value of the discrete Fourier transform (DFT) of the histogram, then the MAC is likely TDMA. Otherwise, the irregular transmit times imply a CSMA MAC.

Control Channel Recognition. The control channel can be in-band, when control packets are time interleaved with data at the same frequency, or out-of-band, when a specific frequency band is used for control packets. Out-of-band control channels typically have low access times because signaling (control) packets are normally short and the channel is not used for data. Recognition can be achieved by clustering two features of each channel: the ratio of devices that have access to that channel over the population of the network and the density of packet transmissions. The greater the percentage of devices accessing the channel and the lower the density of packet transmissions, the more likely it is a control channel. After identifying the control channel(s), specific control packets being used by the network can be recognized by analyzing a histogram of packet lengths and applying a clustering algorithm such as k-means. Note the function of the control packet is not identified.

Results: Two modeling and simulation environments developed at the U.S. Naval Research Laboratory were used to generate data for network learning analysis: Extendable Mobile Ad-hoc Network Emulator (EMANE), which emulates real network behavior, and a Cognitive Radio Framework, developed for creating cognitive radio networks in software-defined radio. Figure 11 shows the learned network groupings, achieving 90% accuracy, and Fig. 12 shows the actual network groupings.

Summary: Blind network inference algorithms are used here to discern which radios are in the same network, which of them communicate, and how they communicate with each other. The learned information includes medium access control type (TDMA, FDMA, or CSMA) and control plane mechanisms, such as the presence of control packets or channels. The characteristics learned here provide an increased level of situational awareness on communication networks of interest.

[Sponsored by ONR]

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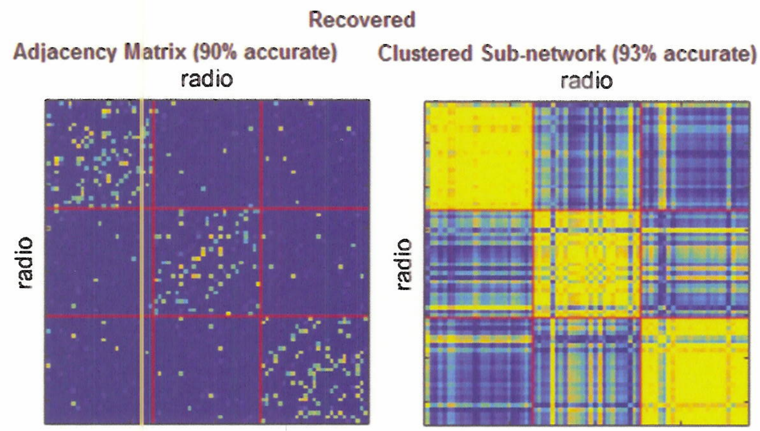


FIGURE 11
Learned adjacency matrix and sub-network cluster for 75 radios and three networks.

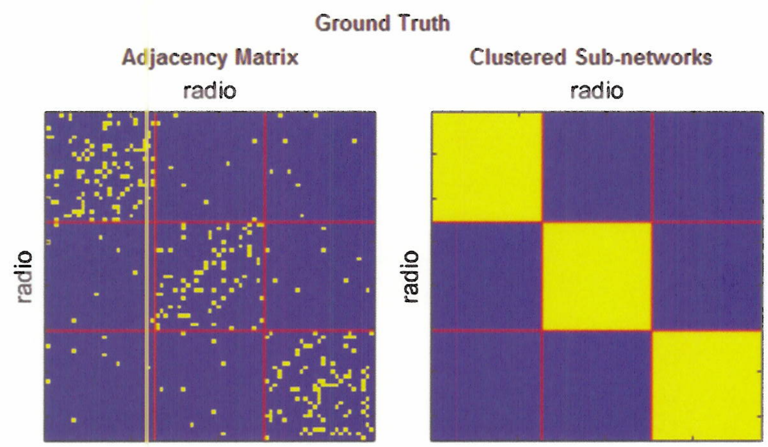
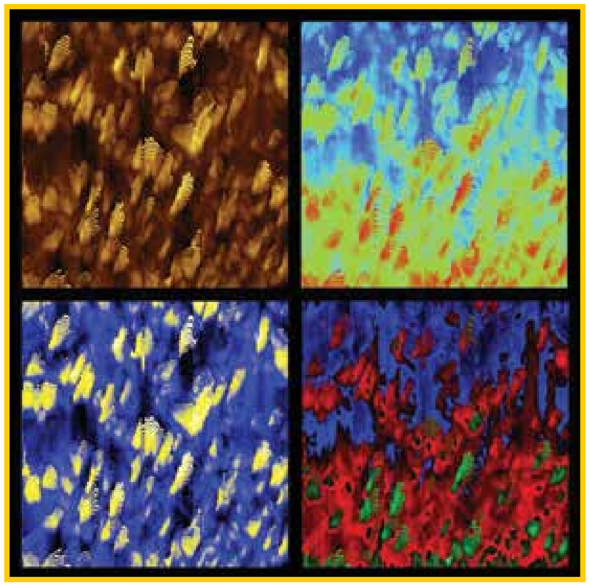


FIGURE 12
Actual adjacency matrix and sub-network cluster for 75 radios and three networks.

Materials Science and Technology

NRL SCIENCE AS ART CONTEST
Chemistry Division Choice



Warhol Meets Atomic Force Microscopy
This atomic force micrograph is of an ultrathin film of ruthenium dioxide (RuO_2) nanoparticulates deposited onto planar silica. The electronic conductivity of these disordered RuO_2 "nanoskins" can be tuned by three orders of magnitude without changing the morphology of the film, providing broadband transparent conductivity that spans the ultraviolet-microwave window, and can even evolve molecular oxygen by splitting water with state-of-the-art performance. Just as the famous 1960s Pop Artist Andy Warhol expressed color differences and repetition to highlight different sensations, false color is commonly used in microscopy to deepen our understanding of what the data represent.

Joseph Parker, Irina Pala, and Debra Rolison
Chemistry Division

Ionic Liquid Gating of Two-Dimensional and Thin Film Materials

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Introduction: The successful development of future nanoscale devices relies heavily on the discovery and characterization of thin film and two-dimensional materials with structure- and charge-carrier-concentration (n)-mediated, metal–insulator transitions (MITs). Indeed, many useful properties often emerge or are modified at the MIT, such as superconductivity (MoS_2, WS_2, $YBa_2Cu_3O_{7-\delta}$), IR transmission (VO_2), and quantum Hall effects (graphene). The location of the MIT in parameter space and the material properties can be tailored during synthesis via chemical doping, and later controlled during device operation via electrostatic gating. However, doping and intercalation can adversely affect the structure of layered materials, and the maximum achievable n is limited by the gate barrier breakdown voltage; these are issues that obstruct studies of the MIT and 2D superconductivity, and leave the materials underutilized.

The newly pioneered technique of ionic liquid (IL) gating overcomes these obstacles and promises to open a new avenue of research aimed at discovering new phenomena in conventional and novel material systems alike. For example, it has been shown recently that electric-field gating the band insulator MoS_2 with an IL-dielectric prompts a superconducting transition that previously was only known to occur after intercalating it with alkali- or alkali-earth metals,[1] a process that extrinsically affects its layered structure. Meanwhile, the renowned chemical inertness of epitaxial graphene makes it difficult to deposit a dielectric layer on its surface and fabricate a conventional top-gated field-effect device, hampering the study of its electrical properties at different Fermi energies. However, as we show, the unique arrangement of sample, dielectric, and gate terminal in an IL gating experiment allows this measurement to be conducted with relative ease.

Concepts: Ionic liquids are a diverse class of salts that have melting points near or below ambient temperatures. In addition, they are electrically insulating/ionically conductive and have negligibly low vapor pressures. The diagram in Fig. 1 demonstrates how a droplet of IL is used to modulate the charge density of an n-type sample prepared in a field-effect transistor configuration. The IL droplet is dispensed so that it completely covers both the conductive channel of the sample and an electrically isolated, co-planar gate terminal. Now, if an electric potential (V_g) is maintained between the gate and the drain, the cations and anions of the IL will move to opposite terminals; for a positive V_g, cations (anions) accumulate in a layer on the surface of the channel (gate), and vice versa for negative V_g. Interestingly, at this liquid/solid interface, the potential drops over a mere distance of ~1 nm, leading to an extremely high capacitance (~10 μF/cm^2) despite the moderate dielectric constant of the IL.[2] Thus, only a few volts are required to attract electrons toward the channel surface in sheet densities over 10^{14} cm^{-2}. Care must be taken to protect exposed metal leads from direct contact with charged ILs due to the risk of galvanic corrosion. However, once below the glass transition temperature of the IL, virtually all chemical reactions cease and the ions are immobilized, meaning the gate potential will remain poled even after the voltage source is removed.

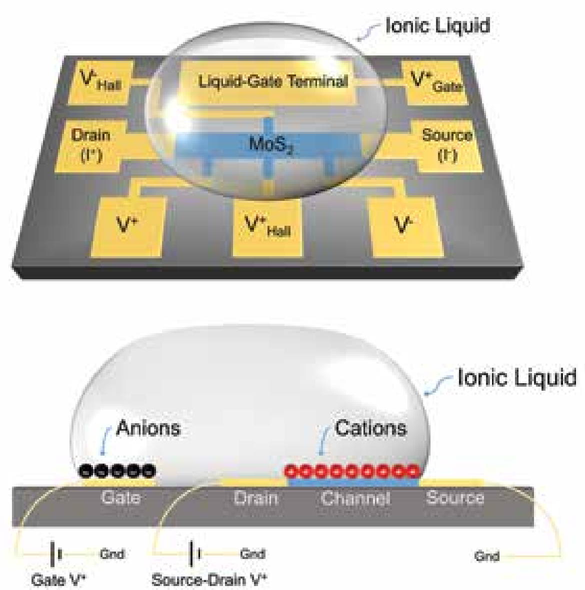

FIGURE 1
Device layout (top) and schematic (bottom) of an IL gating experiment with MoS_2.

Research at NRL: At the U.S. Naval Research Laboratory, we are in the initial stages of using the IL gating strategy to investigate novel electrical transport properties in a variety of 2D and thin film materials (e.g., MoS_2, graphene, VO_2). This work involves a multidisciplinary effort among (a) chemists, with expertise in the synthesis of custom, air-stable ILs and IL gels; (b) nanofabrication scientists, to properly engineer devices that can tolerate the extreme parameters of the experiments; and (c) materials scientists, to determine the nature of the MIT in 2D, thin film, and layered materials, and identify new material properties and their potential applications.

One of our main goals is to perfect the IL gating technique to study various types of epitaxial graphene and develop new quantum Hall–based resistance standards and sensors.[3] The preliminary results displayed in Fig. 2 show the sheet resistance (R_s) versus V_g at T = 300 K for an epi-graphene sample grown by thermal sublimation from an SiC substrate. The peak in the sheet resistance of value $R_s \approx h/4e^2$ that occurs at $V_g = -0.7$ V is a clear indication that we have successfully shifted the Fermi energy of our graphene through the Dirac point using IL gating.

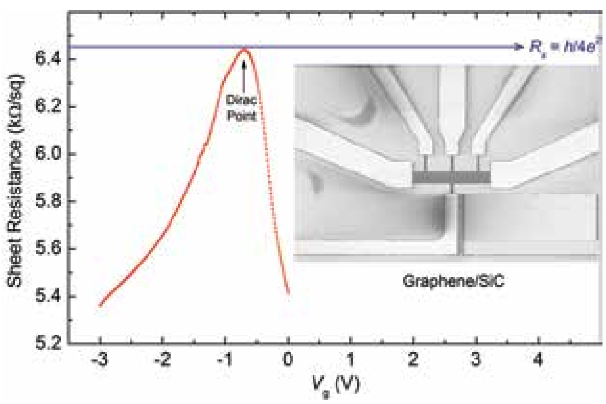

FIGURE 2
Sheet resistance versus IL gate voltage at T = 300 K of epitaxial graphene on SiC substrate. Inset: SEM image of the device.

We are now using this methodology to perform comprehensive, temperature-dependent magneto-transport measurements and build a better understanding of the quantum Hall effects in epi-graphene. In addition, determining the role of disorder and/or increased e-e interactions on the 2D nature of the superconductor–insulator transition of MoS_2 is a high priority. Furthermore, we aim to conclusively settle the debate as to whether the electrostatically driven MIT in VO_2, which has only been accomplished via IL gating, is indeed electrostatic (i.e., *n*-dependent) or electrochemical (i.e., E-field induced O vacancies) in nature.

Acknowledgments: This work was performed while J.C. Prestigiacomo held a National Research Council Research Associateship at NRL. This is a cooperative effort between the Materials Science and Technology Division and the Electronics Science and Technology Division.

[Sponsored by the NRL Base Program (CNR funded)]

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Desensitization of AA 5456 Alloy Plate with Pulsed Electron Beam

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Heat Sensitization: Aluminum-magnesium alloys with around 5% magnesium are important ship structure alloys because they exhibit excellent resistance to general corrosion and high as-welded strength. However, these alloys become susceptible to stress corrosion cracking if exposed to temperatures above 50 °C for extended periods of time. This phenomenon, known as heat sensitization, is a consequence of the diffusion of magnesium to the grain boundaries, where it forms β-Al_3Mg_2 phase. β phase in the alloy corrodes and dissolves very quickly upon exposure to seawater, leading to severe structural cracking. We have described[1] basic research at the U.S. Naval Research Laboratory directed at understanding the phenomenon and its detrimental effects on ship structure alloys.

In the laboratory, heat sensitization can be reversed by heating the material near 300 °C for short periods of time. This causes the β phase to dissolve, and the magnesium to diffuse back into the bulk of the alloy. Unfortunately, it is not possible to heat a ship structure to 300 °C without causing other structural damage and damage to sensitive equipment inside the ship. However, a way of controllably heating localized areas for short periods of time may be practical for shipboard desensitization.

Pulsed Electron Beam Treatment: NRL has explored the use of high voltage pulsed electron beam (PEB) to provide the desired localized, short duration heating.[2] Such an electron beam can be projected onto a selected area. Heating occurs as the electrons penetrate deeply into the material. The depth of penetration is controlled primarily by the beam voltage. The heating rate is controlled by a combination of the PEB current

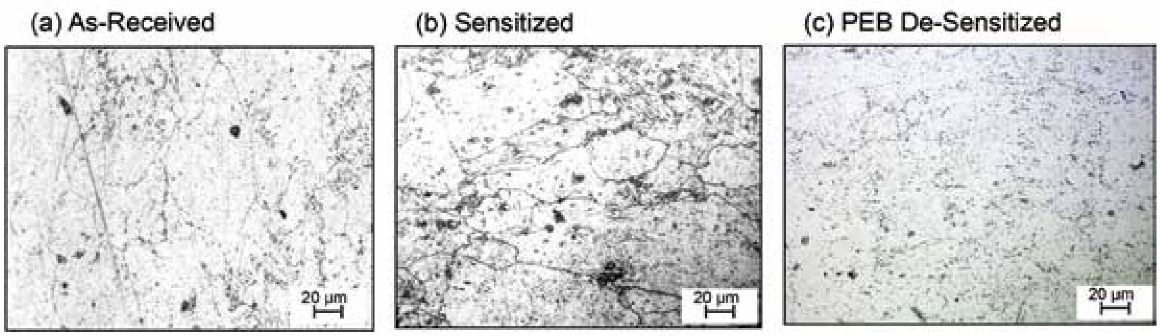

FIGURE 3
Effect of pulsed electron beam treatment on sensitization. Dark grain boundaries indicate high concentration of Al_2Mg_3 phase. (a) As-received 5456 alloy. (b) Highly sensitized (aged at 100 °C for 12.5 days). (c) After pulsed electron beam treatment.

density per pulse, the pulse rate, and the total number of pulses applied to a given location.

Figure 3 shows the effects of a PEB on 5456 marine service aluminum alloy. These samples were polished and acid etched, which causes grain boundaries with β phase to appear dark. Figure 3(a) is the as-received condition. Even as it comes from the manufacturer, there is considerable amount of β phase present. Figure 3(b) shows a sample with a very high degree of sensitization. Almost all of the grain boundaries are continuously covered with β phase. Figure 3(c) shows a sample that was first sensitized to the same degree as 3(b), then subsequently treated with the PEB. Nearly all of the β phase has disappeared, and it appears there is even less than in the original as-received material from the manufacturer.

Figure 4 shows a very interesting effect. The horizontal dashed lines indicate two levels of sensitization usually used for evaluating marine service alloys. A degree of sensitization (DOS) below 15 mg/cm² is generally considered to be acceptable for a ship construction. DOS in excess of 25 mg/cm² is considered to be high risk for structural degradation. The material shown in the figure has an initial DOS of 6 mg/cm² as received from the manufacturer. When heated at 100 °C, DOS increases over time, and within 3 days at 100 °C, it exceeds the threshold of 15 mg/cm², and at 6 days, it exceeds the 25 mg/cm² threshold. The same material after PEB desensitization has a DOS of effectively zero for up to 7 days of heating, and does not reach 15 mg/cm² until nearly 10 days, more than a factor of 3 increase in initial sensitization life. DOS does increase more rapidly after that, but it still takes nearly twice as long to reach the danger level than the as-received material. This suggests PEB treatment may be useful as a post-manufacturing treatment, in addition to being a repair technique.

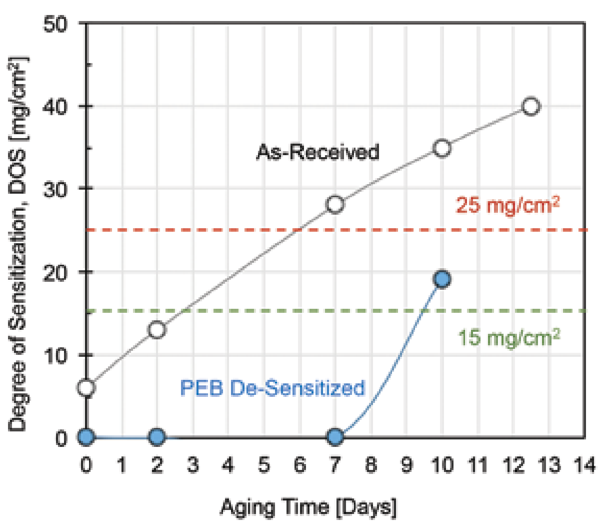

FIGURE 4
Aging behavior before and after pulsed electron beam treatment. The degree of sensitization (DOS) units are mg/cm² and indicate the amount of mass lost by a specimen in the ASTM G-67 standard intergranular corrosion test.

Application Concept: There are technical challenges to overcome to transition this technology into a fieldable system. The laboratory experiments use a room-size electron beam system. Although that might be suitable in a manufacturing environment, to be used on a ship, the system must be portable. We believe it should be possible to engineer an electron beam system roughly the size of a 55 gallon drum, depicted conceptually in Fig. 5. Another challenge is to develop an electron beam "window" material for the system. The electron beam is generated in a vacuum, while the surfaces to be treated are in air. To avoid having to seal the system against the surfaces to be treated, a "window" must be thin enough to allow the electron beam to pass through, but structurally sound enough to withstand atmospheric pressure on the outside with vacuum on the inside.

Significance: A portable system for desensitization of ship structures, with precise thermal and spatial control, may be an alternative to cutting out and replacing sensitized plating. The possibility of using pulsed electron beam to reduce sensitization in manufactured plate, even before it is installed on a ship, suggests the

(a) (b)

FIGURE 5
(a) The Electra pulsed electron beam system in the NRL Plasma Physics Division used for the proof-of-concept experiments. (b) Conceptual portable electron beam system for shipboard desensitization treatment. The system must be small enough to fit through bulkheads. Horizontal surfaces could be treated by rolling the system around on the deck. Vertical surfaces could be treated using an articulated lifting system as suggested in the figure.

possibility of improving even the initial lifecycle of ship structures.

[Sponsored by ONR and the NRL Base Program (CNR funded)]

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The Quest for an Intense X-ray Source from a Gas-Puff Pinch

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Plasma Physics Division

Introduction: Pulsed power generators produce currents in the range of hundreds of kiloamperes to multi-megaamperes over a timescale of approximately 100 nanoseconds to microseconds. There are a variety of loads for the generator to drive. In the case of a gas-puff load, such as argon or deuterium, the gas is released from a plenum through a nozzle to form a jet and/or an annular shell. The generator's rapid current pulse leads to an electrical breakdown of the gas, and the subsequent interaction of the axial current density (***J***) and the azimuthal self-magnetic field (***B***) causes the plasma to implode upon itself, or "pinch," as illustrated in Fig. 6. The result is a hot, dense plasma that radiates X rays (>3 keV for Ar) or produces neutrons (2.4 MeV for deuterium) for approximately 10 nanoseconds. The implementation of gas puffs as an efficient and copious radiation source encountered major challenges, particularly disruptive instabilities. These challenges were largely overcome thanks to a nearly four-decade-long experimental and theoretical effort by a large number of researchers, including scientists from the Radiation Hydrodynamics and Pulsed Power Physics branches at the U.S. Naval Research Laboratory. Today, the gas-puff Z-pinch has evolved into a powerful source for X rays and neutrons. A recent review by NRL personnel documents the basic physics, experimental development, and theoretical understanding of this long enterprise.[1]

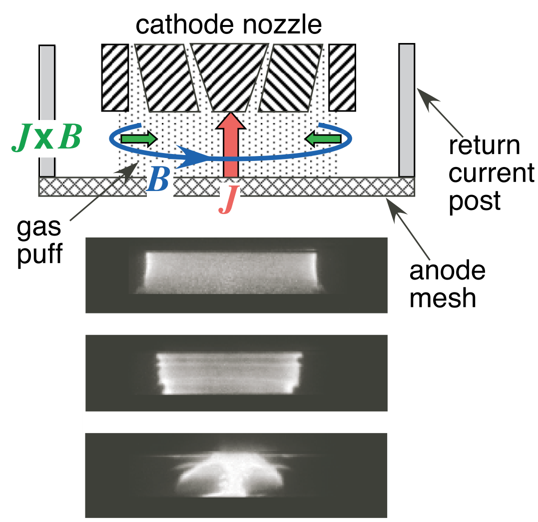

FIGURE 6
At top is a schematic drawing of a gas-puff Z-pinch with the basic hardware and electromagnetic components. Below are successive images of the initiation, implosion, and stagnation stages of a pinch. Images from Ref. 2.

The Challenge: The first gas puff was fielded on a small university generator in the late 1970s. Quickly there followed a number a papers on the use of gas puffs for spectroscopic study of highly ionized noble gases, electron beam generation, radiation, and neutron production. An intense source of X rays, particularly from ionized Ar with one or two remaining bound electrons (K-shell) became the primary objective. To obtain Ar in this state requires converting the stored energy in the generator to a high electron temperature. The electrical energy from the generator is coupled to the gas through the Maxwell stress, commonly referred to as the "$\boldsymbol{J}\times\boldsymbol{B}$" force (see Fig. 6). For a thin shell, the coupled energy, $E_{J\times B}$, is simply the kinetic energy of the total imploding mass, M. When the plasma pinches and stagnates on axis, this coupled energy is converted into electron and ion thermal energy. If the coupled energy per load mass, $E_{J\times B}/M$, is sufficiently large, then electron thermal collisions can produce K-shell ionization stages along with the associated X-ray radiation. For a fixed implosion time and peak generator current, $E_{J\times B}/M$ scales predominantly as the square of the initial radius. However, the large radius allows more rapid growth for the Magneto-Rayleigh-Taylor (MRT) instability that can disrupt the implosion and convert much of the energy of inward radial motion and compression into turbulence, rather than thermal energy. This instability can be seen to develop in Fig. 6. Theoretical research, including at NRL, proposed that specially tailored gas density profiles could be used to mitigate the MRT instability. An example from numerical simulations is shown in Fig. 7.[2] Over the region where the density profile has a strong power law falloff in radius (the inset in the figure), the instability can be damped. This is exemplified by the low value for the axial kinetic energy compared to the radial kinetic energy.

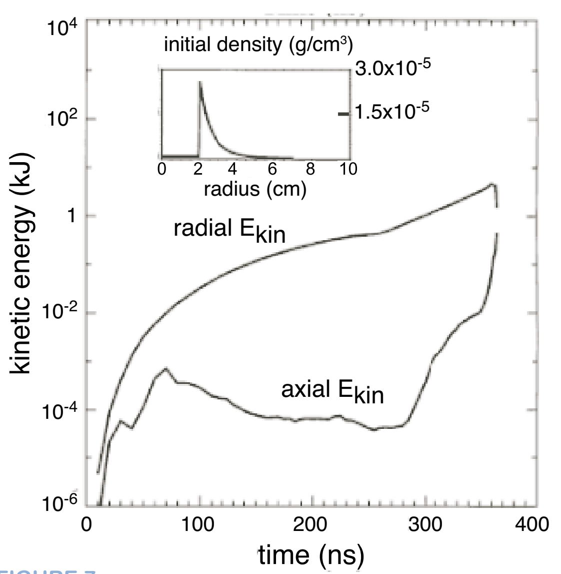

FIGURE 7
Simulated results for the stabilization against the MRT instability (radial kinetic energy > axial) for the tailored density profile shown in the inset.

Results: A number of different initial radial density profiles for the neutral gas were experimentally obtained by employing various nozzle designs including single shell, double shell, and double shell with a center jet. Figure 8 summarizes the results covering more than 30 years for the K-shell yield from Ar on a number of different generators with either a short current pulse (<150 ns) or a long one (>150 ns). Long implosion times generally reduce some design constraints for pulsed power generators but require larger initial radius to maintain large $E_{J\times B}/M$. The results show that the MRT can be mitigated for large initial radius by appropriately tailoring the initial radial density profile. In the inefficient regime of low current, the K-shell yield is a small fraction of $E_{J\times B}$ and scales as the fourth power of the generator current (I^4). However, as one moves to high current generators, the K-shell yield is approximately one third of $E_{J\times B}$ and scales as I^2. Energy conservation dictates that radiation output cannot exceed the energy coupled from the generator, which varies as I^2. These same considerations of tailored profiles leading to stable implosions have been applied to deuterium gas puffs to produce plasmas of a few kiloelectron-volts temperature with significant neutron production from deuterium-deuterium (D-D) reactions.

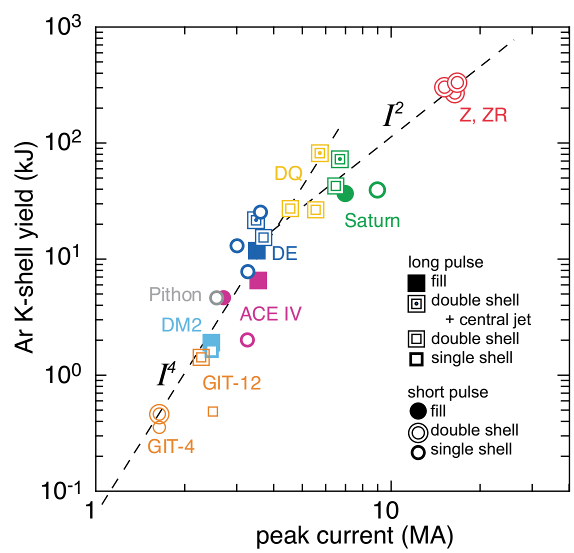

FIGURE 8
The K-shell yield from argon (>3 keV) versus the peak gas-puff Z-pinch current. The graph is a summary of more than three decades of improvements in pulsed power and Z-pinch design. The historical record parallels the abscissa from left to right. Various generators on which the experiments were performed are named in color and the particular Z-pinch gas-puff load design is indicated by the symbol.

Significance: Important applications of these sources necessitate a hot, dense plasma be formed at stagnation and that this state persist for sufficient time to produce the desired output. Gas-puff Z-pinches are used in fundamental studies of the atomic physics of highly ionized species, high energy density physics, X ray and neutron sources, and laboratory tests for survivability of components in space-based military systems against nuclear threats.

[Sponsored by the the Dept. of Energy National Nuclear Security Administration and the NRL Base Program (CNR funded)]

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Nanoscience Technology

NRL SCIENCE AS ART CONTEST

Material Science and Technology Division Choice

Falling Waters

Additive manufacturing (AM) is a name for technologies that build three-dimensional objects through a layer-by-layer deposition of material. Often called 3D printing, AM could revolutionize small-lot production (the manufacture of a small number of items of the same type and design). But much still needs to be understood about how the complex grain structures of AM-produced material influence the properties of the material. NRL researchers in the Materials Science and Technology Division used a scanning electron microscope with electron backscattered diffraction to produce this 500- by 500-micrometer image of the crystal orientations and structures in a vertical slice of AM-produced marine-grade (SAE 316) stainless steel. The large and elongated grains depicted here, with their curved and irregular shapes, resemble flowing water. The grains of conventionally manufactured material are much more uniform in size and shape.

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Material Science and Technology Division

Single-Atom-Sensitivity Imaging and Spectroscopy

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Materials Science and Technology Division

Atom-by-Atom Design: In the future, new optical and electronic devices will employ materials designed, produced, and operated with atom-by-atom precision. For example, the electrical and optical properties of graphene and other two-dimensional (2D) materials have the potential to be tuned by the incorporation of individual ad-atoms and substitutional impurities. Similarly, the properties of many nanoparticles, such as quantum dots for use as q-bits in quantum computers, can be altered by incorporation of individual dopant or impurity atoms. A critical step in making atom-by-atom device design a reality is the ability to characterize the component materials with single-atom sensitivity. That is, to achieve the desired properties, researchers need to be able to image and spectroscopically confirm that each atom is what and where it is supposed to be. With the delivery of a new Nion UltraSTEM aberration-corrected scanning transmission electron microscope (AC-STEM), researchers in the Materials Science and Technology Division at the U.S. Naval Research Laboratory (NRL) can now do just that: materials imaging and spectroscopy with single-atom sensitivity.

A Leap in Resolution: Transmission electron microscopy has long a been a staple of materials characterization for imaging at scales of microns down to individual atomic columns, and analysis of materials composition at scales down to 1 nm. However, the incorporation of aberration-corrected electron optics into the latest microscopes provides an order of magnitude improvement in both sensitivity and spatial resolution. With these new microscopes, it is finally possible to see the carbon atoms in a single graphene sheet, and other materials with subnanometer resolution. Not surprisingly, these capabilities are being rapidly adopted in laboratories worldwide.

What really sets the new NRL AC-STEM apart from other advanced electron microscopes is its unique large-collection-angle, energy dispersive X-ray detector. Using this EDXS detector, the authors set a new world record for X-ray detection of single atoms in as little as 8 seconds.[1] The sample we analyzed was a material containing a mixture of amorphous carbon and nanodiamonds, with a wide variety of incorporated impurity atom species. Similar materials, with better controlled impurity distributions, may be adopted for use in quantum computers or in biological imaging applications in the future. The impurity atoms appear as bright dots in the dark-field AC-STEM images. By controlling the electron beam to raster in a box tightly positioned around the impurity atom of interest, and then collecting induced X-ray signal from the atom, we were able to identify single Si, S (Fig. 1), P, and Ca impurities.

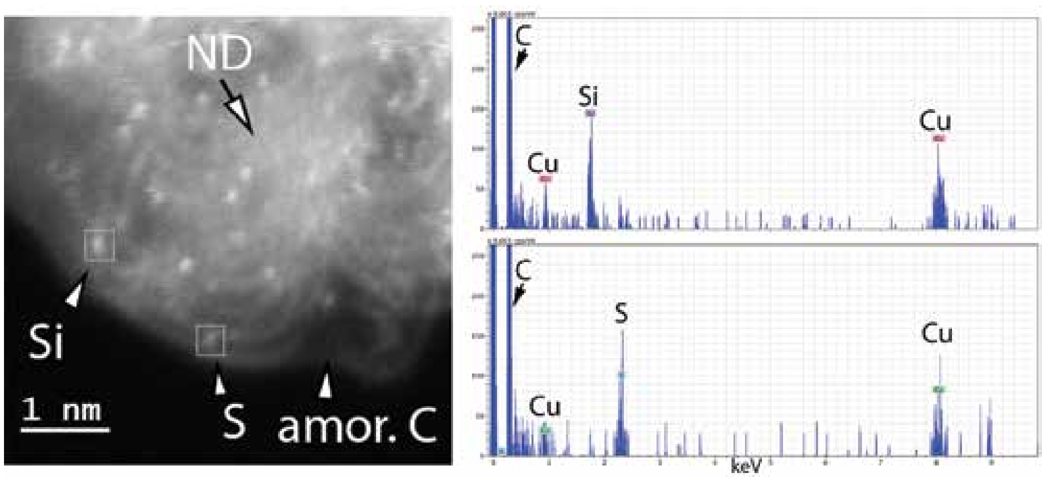

FIGURE 1
Annular dark-field image (left) and energy dispersive X-ray spectra (right) from an amorphous carbon and nanodiamond (ND) sample. The white dots are individual impurity atoms. The Si atom was identified in 9 seconds and the S atom in 8 seconds.

New Materials Possibilities: The single-atom EDXS capability is equally important for development of 2D materials, such as graphene, MoS_2, and phosphorene. These materials show promise for development as low-power, flexible electronic materials. However, their properties depend strongly on modification with individual dopants, and researchers need to be able to control that modification. With the Nion UltraSTEM, we have shown that Si atoms are often left as residual contaminants from adventitious hydrocarbons introduced during growth and processing (Fig. 2). This new capability to see and identify the beneficial dopants, as well as the accidental impurities, is now being put to use in 2D materials research efforts across NRL, including in the Electronics Science and Technology, Chemistry,[2] and Plasma Physics Divisions. Other potential applications include mapping of DNA-based nanomaterials developed in NRL's Center for Bio/Molecular Science and Engineering.

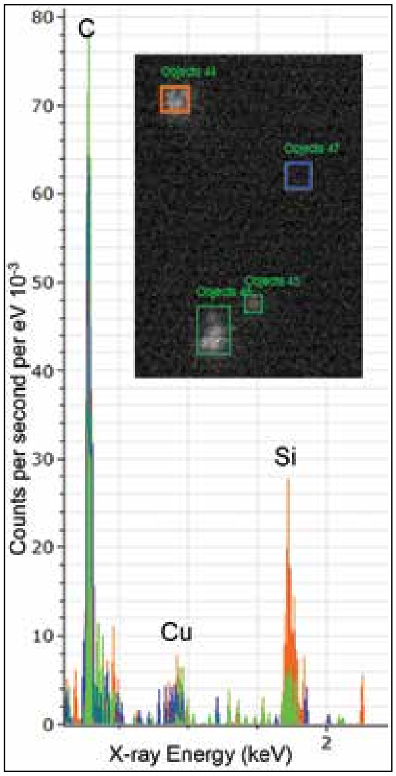

FIGURE 2
X-ray spectra and dark-field image (inset) from 0 (blue), 1 (green), and 3 (orange) silicon impurity atoms on graphene. The Cu signal is from the sample support.

Acknowledgments: The Nion UltraSTEM with Bruker EDX detector was acquired with NASA and NRL (Code 6000) capital equipment funds. We are extremely grateful to the NRL Institute for Nanoscience staff for their contributions to maintaining the strict environmental conditions necessary for the UltraSTEM to provide single-atom sensitivity performance.

[Sponsored by the NRL Base Program (CNR funded)]

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Energy Manipulation in Graphene Resonators

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Introduction: Understanding and exploiting the connection between atomic-level defects and mechanical properties is a long-standing goal in materials science, as defect engineering is a proven tool for optimizing the performance of many systems. In the field of two-dimensional (2D) crystals, the defect–property relationship can lead to interesting new phenomena not observed in classical three-dimensional materials. Beyond altering elastic constants, defects in 2D systems can diffuse and rearrange themselves to form new fascinating structures that can induce long-range distortions to the crystal lattice and provide an effective mechanism for storing mechanical energy. The emblematic 2D material, graphene, is a single atomic layer of carbon atoms comprised of strong sp^2-carbon bonds that give it the highest measured strength of any material. The work reviewed here describes a direct observation of amending mechanical properties of graphene nanomechanical resonators by introducing and rearranging defects. We demonstrate different pathways in which the net mechanical energy can be changed through defect formation, migration, and/or annihilation. We interpret controllable changes in the dynamical response of graphene resonators in terms of how structural defects (e.g., vacancies/interstitials) and chemical defects (e.g., fluorine functionalization) affect the graphene lattice.

Mechanical Test Structures: Membrane-type (or "trampoline") nanomechanical resonators were fabricated using two different types of graphene. For one source, we utilized mechanical exfoliation of few-layer graphene from bulk graphite, and for the other source, we used chemical vapor deposited (CVD) graphene. Figure 3(a) shows multilayer graphene mechanically exfoliated over circular wells etched into an SiO_2/Si surface, forming circular drum resonators with diameters ranging between 1 and 5 µm. To intentionally introduce defects into these resonators, we exposed the samples to 300 eV Ar^+ ion implantation to controllably form vacancy, interstitial, and cross-linking type defects. Figure 3(b) shows another type of resonator device: a three-layer CVD graphene film transferred onto a silicon-on-insulator (SOI) substrate. Irrigation holes (1–5 µm) were etched through the CVD graphene films to expose the underlying SOI substrate and then etched with xenon difluoride (XeF_2) gas to undercut the silicon support layer. As a result, large suspended graphene resonators (diameters 5–20 µm) were formed. The XeF_2 treatment was also used to introduce fluorine functionalization on graphene.

These two types of graphene systems offer a palette of different defect types (i.e., structural and chemical) that can be introduced and manipulated to affect the mechanical response of graphene resonators. The overall defect density can be probed using Raman spectroscopy (Fig. 3(c,d)). The Raman spectra in Fig. 3(c) were acquired on a graphene resonator before and after ion implantation, highlighting the emergence of the "D peak" (at 1350 cm^{-1}) that is associated with defect formation in the sp^2-bonded carbon layers. We further manipulate (or rearrange) these defects using a laser-annealing protocol wherein a sharply focused laser beam can locally heat the suspended film up to approximately 1000 °C. Figure 3(d) shows a Raman map of the sample (same area as in Fig. 3(a)) after ion implantation and selective laser annealing of particular drum resonators (for example, see drum outlined by black box in Fig. 3(a,c)). From the variation in the full width at half maximum (FWHM) of the D peak shown on the map, it is evident that laser annealing can provide drastic and spatially localized changes to the defects state within the material.

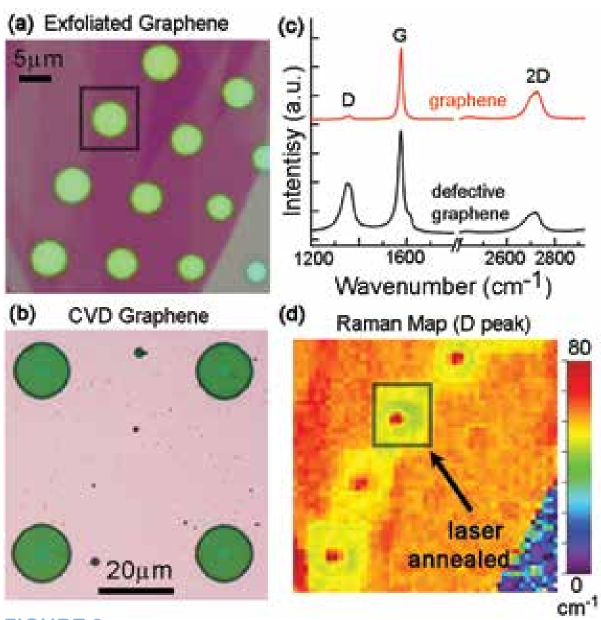

FIGURE 3
Mechanical drum resonators formed from (a) mechanically exfoliated graphene and (b) CVD grown graphene. Their defect state was evaluated using Raman spectroscopy as shown in (c). The Raman map in (d) reveals that laser annealing can locally change the defect population (scale bar: the D peak full width at half maximum, FWHM). The black box drawn in (a) and (d) highlights a region surrounding one resonator that was laser annealed.

Defects and Mechanical Energy: The energy stored in a mechanical device generally manifests itself as mechanical stress (consider the bent limbs of a drawn crossbow). To understand how each defect type influences the stored mechanical energy within the graphene resonators, we extract the value for the mechanical stress from the resonator's fundamental frequency and subsequently perform laser annealing to locally modify the defect states. The resonant frequency (f_0) is directly related to the in-plane tension (for a given geometry), and to measure f_0 we use well-established optical techniques that utilize low laser power thermoelastic drive and interferometric readout for the mechanical motion. An additional third laser is employed as an "annealing" tool that can be independently controlled and positioned in order to locally generate high energy states within the suspended structures (Fig. 4(a)).

We demonstrate that the presence of chemical defects (i.e., fluorine functionalization) or structural defects (e.g., vacancies and interstitials) provides a powerful tool that allows one to tailor the frequency response and, therefore, the stress state of the graphene resonators. Laser annealing of Ar^+ implanted resonators results in f_0 monotonically decreasing (stress release) with increasing annealing laser power (Fig. 4(b), red squares). Performing the same experiment on fluorine-functionalized resonators results in the opposite frequency shift, wherein f_0 monotonically increases (stress buildup) with increasing laser power (Fig. 4(c), black squares). As a control experiment, defect-free resonators showed no change in f_0 even with high power laser annealing, which is expected for these structures (Fig. 4(b), blue triangles).

To explore the time evolution of defects and ability to store mechanical energy within the resonator in a dynamic way (akin to charging and discharging a battery), we carried out time-resolved resonant frequency measurements. By continually acquiring frequency spectrum of the mechanical vibrations while turning the laser annealing beam ON and OFF, we observe how the resonator stiffness (i.e., spring constant) is affected by the motion and annihilation of defects. Figures 4(c) and 4(d) show data acquired using an exfoliated graphene resonator before (c) and after (d) Ar^+ implantation. Turning the annealing laser beam ON creates tensile stress in both resonators. But when defects (vacancies and interstitials) are present and "activated" by the laser anneal (Fig. 4(d)), they act to prolong the resonator's "stressed-out" state even after the annealing beam is turned OFF. Analogous to a wind-up toy, the defects help the resonator to slowly dissipate its energy once it has been "wound up" by the laser anneal.

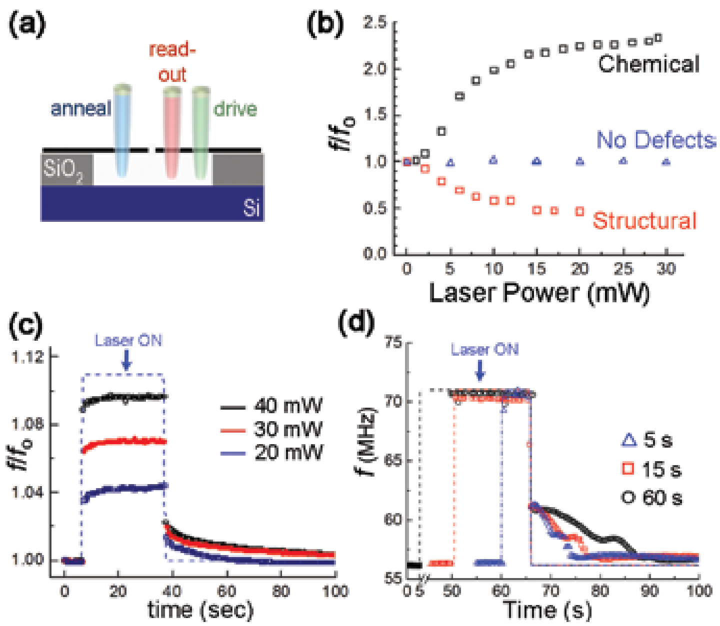

FIGURE 4

(a) Schematic showing a graphene drum resonator together with the three lasers used to perform resonance experiments (not to scale). (b) Plot of normalized frequency (f/f_0) vs laser-annealing power for an as-exfoliated graphene resonator (blue) and a subsequently Ar^+ implanted resonator (red) and a fluorinated resonator (black). (c) Plot of normalized frequency (f/f_0) vs time for a defect-free exfoliated graphene resonator. The dashed line indicates the period when the annealing laser was ON and OFF while taking frequency measurements. (d) The frequency response of an exfoliated graphene resonator that has structural defects. The longer frequency relaxation time highlights that defects influence the stored mechanical energy in the system. The annealing laser was turned ON for three different times as labeled.

Looking Ahead: The ultimate scaling limit for solid-state mechanics can be reached using 2D crystals such as graphene. The nanomechanical resonators studied here demonstrate that the role of defects is crucially important in materials that are only a few atoms thick. The ability to actively control defects and to locally manipulate the mechanical stress using tools like laser (or even electron) beams will enable new opportunities for actuating nanomechanical devices. Perspectives for storing mechanical energy and releasing it on demand can be even more far-reaching. As a next step, we envision a new platform of nanoscale devices wherein their electrical and optical properties are controlled through the synergy of mechanics and defect engineering.

[Sponsored by the NRL Base Program (CNR funded)]

Nanocrystalline Silicon for Thermoelectric Power

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Introduction: Thermoelectric materials, which generate electricity directly from heat or use electricity for refrigeration without moving parts, can play an important role in many critical Navy applications. This technology could greatly improve the fuel efficiency of Navy warships and unmanned underwater vehicles by converting waste heat from traditional power sources into useful energy. In addition, ocean thermal energy may be directly converted into electricity by siphoning heat from the natural temperature difference between shallow and deep ocean water. In a more general sense, thermoelectric materials may also be part of a global sustainable energy solution by converting waste heat into electricity on a massive scale.

While all semiconducting materials have a non-zero thermoelectric effect, in most materials it is too small to be useful. The thermoelectric efficiency of a material is closely related to the material's ability to generate a voltage in response to a temperature gradient, called thermoelectric power. The ideal thermoelectric material will also have a high electrical conductivity to avoid self-heating and at the same time a low thermal conductivity to maintain the temperature difference. As these material parameters are interdependent, one big challenge is to reduce thermal conductivity by scattering phonons without simultaneously scattering charge carriers. The conventional techniques used to get around this challenge have not been particularly successful; among them, the most effective is a process called ball-milling, in which doped crystalline Si is ground together with a small percentage of Ge into a powder, which is then hot-compressed into a bulk nanocrystalline material.[1] The resulting materials contain mostly crystalline grains of the size of tens of nanometers, which increases both phonon and charge carrier scattering. While thermal conductivity is reduced, the charge carrier transport can be rejuvenated by increased doping of P or N type dopants during milling. However, since the smallest grain size that ball milling can obtain is about 10 nm — not small enough to scatter short-wavelength phonons that transport most of the heat above room temperature — additional, smaller-scale phonon scattering must be introduced. The conventional solution is to add Ge to generate impurity scattering centers for short-wavelength phonons. However, Ge is 1000 times more expensive than Si, resulting in much higher production cost. Additionally, Ge compromises the charge carrier transport and reduces the useful temperature range of the device by 150 to 200 °C due to the low melting point of the SiGe alloys.

Nanocrystalline Si with Ultrafine Grain Sizes by Chemical Vapor Deposition: In this work, we report an innovative plasma-enhanced chemical vapor deposition (PECVD) technique to deposit thin film nanocrystalline Si (nc-Si). By diluting silane (SiH_4) with hydrogen (H_2), the ratio of which we call $R(=H_2/SiH_4)$, we successfully deposited nc-Si thin films with average grain sizes of about 3 nm and achieved a record low thermal conductivity for any type of Si. It is known that using hydrogen dilution, one can deposit nc-Si. However, this is the first time that nanocrystalline materials with such fine grain sizes have ever been produced.

One of the advantages of our thin film approach is that we can vary grain sizes by changing *R* during deposition to produce a layered structure, thereby scattering a broad spectrum of phonons. Figure 5(a) shows a designed multilayered structure, and Fig. 5(b) shows the X-ray diffraction peaks (111) of three different thin films produced with different values of *R*. Analysis of the peaks shows that the average grain sizes are approximately 3 to 5 nm. Figure 5(c) shows the dark-field scanning transmission electron microscope (STEM) image of the multilayered thin film with alternating R=80/100. Each layer is about 5 nm thick. Figure 5(d) shows the atomic resolution dark-field STEM image of a film with R=100. Individual grains with random orientations and average sizes of about 3 nm are clearly visible. Figure 6 shows the thermal conductivity of our thin films in comparison with other crystalline Si materials. We know thermal conductivity decreases with decreasing material dimensions/grain sizes. Shown from top to bottom are thermal conductivities of bulk crystalline Si, single crystalline thin films and nanowires, nc-Si prepared by the ball milling technique, and our PECVD nc-Si. The solid red curve is the theoretical minimum thermal conductivity of Si calculated using the smallest possible phonon mean path.[2] The thermal conductivity of amorphous Si typically has a value close to the theoretical minimum. As we vary *R* from 35 to 80–100, the thermal conductivity of our nc-Si drops below the theoretical minimum. In fact, the lowest thermal conductivity we achieved is only a third of that. This result demonstrates that our ultrafine grain sizes not only significantly reduce the phonon mean free path, but also change the phonon band structure in a way that results in a reduction of phonon transport speed which is not taken into account in the minimum thermal conductivity calculation.

Thermoelectric Properties and Benefits: We further show that we can use ion implantation and annealing to add dopants into the material to reach thermoelectric power and electrical conductivity values competitive with ball milled materials.[3] The fabrication processes of our nc-Si thermoelectric thin films, including CVD, ion implantation, and annealing, are all compatible to general Si-based large area integrated circuit manufacturing processes. In comparison with other thermoelectric approaches, nc-Si can be prepared inexpensively at large scale and can be used at 1000 °C and above.

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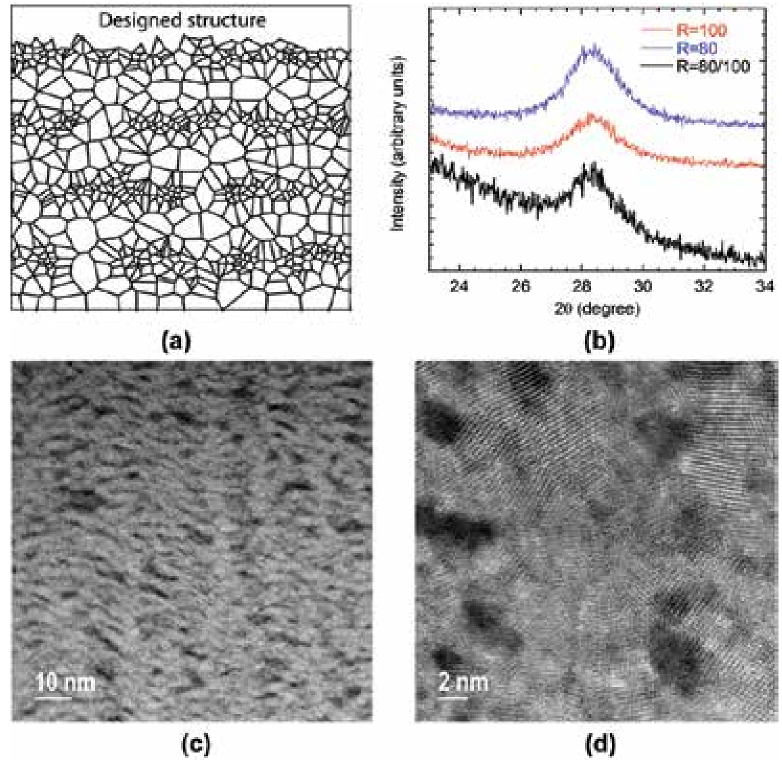

FIGURE 5

(a) Sketch of "designed" nc-Si thin film structure with varying grain sizes. (b) X-ray diffraction pattern of (111) peak of three PECVD nc-Si materials with different H_2 dilution ratio *R*. (c) Dark-field STEM image of a multilayered nc-Si with alternating *R*=80/100. (d) Dark-field STEM image of a film with *R*=100.

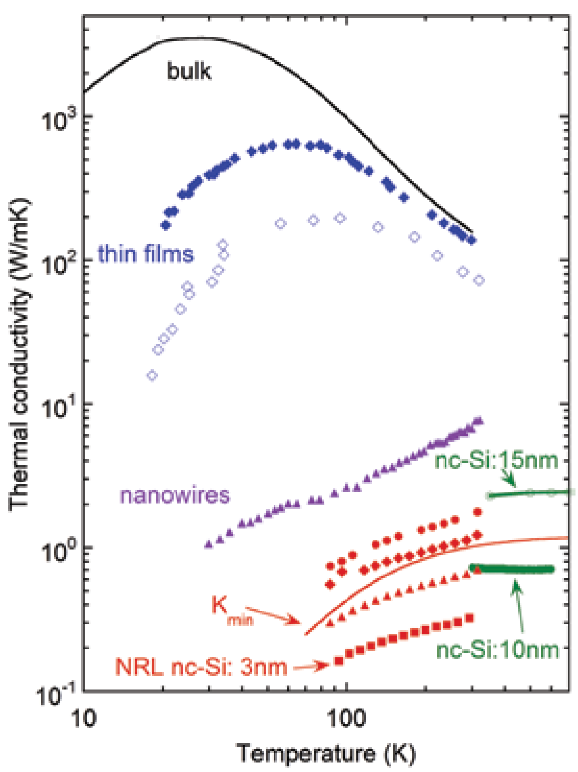

FIGURE 6

Thermal conductivity of various crystalline Si materials. From top to bottom: bulk (black line), thin films (blue), nanowires (purple), ball milled nc-Si (green), and PECVD nc-Si (red) prepared in this work.

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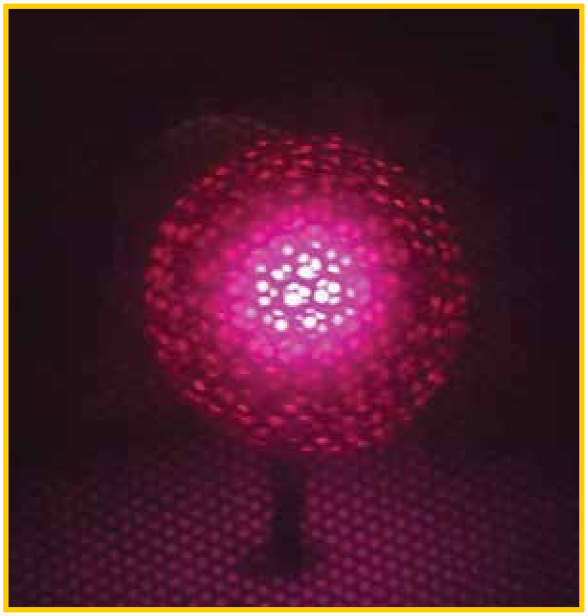
NRL SCIENCE AS ART CONTEST

Plasma Physics Division Choice



Glowing Plasma Cloud in Chamber

A spherical porous cavity resonator (SPCR) traps microwaves, but allows visible light to escape freely, revealing the light emitted in the recombination and relaxation of the enclosed plasma. This image shows the light radiated by a stable plasma cloud within an SPCR driven by a conductive stub inserted in its side. The intensity of the light from the cloud became saturated as the power in the incident microwave fields increased. Also, the microwave frequency for production of the densest and brightest plasma ball shifted as the microwave input power varied. These experimental observations were investigated using a theoretical model of the microwave excited plasma.

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High-Resolution, Regional Arctic Modeling in Support of U.S. Coast Guard and Office of Naval Research Operations

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A New Arctic Modeling System: The U.S. Coast Guard (USCG) and Office of Naval Research (ONR) conducted several Arctic field exercises during the summer and autumn of 2015. In July 2015, the USCG Cutter *Healy* performed operations in the Alaskan Exclusive Economic Zone (Fig. 1, red lines off Alaskan coast) testing new technologies in communications, navigational safety, oil spill tracking, and unmanned vehicles. From August through October 2015, the *Healy* made a cruise to the North Pole as part of the National Science Foundation GEOTRACES program (Fig. 1, red lines to pole). From early October through mid-November, major fieldwork for the Office of Naval Research Sea State Departmental Research Initiative was conducted aboard the R/V *Sikuliaq* (Fig. 1, blue lines).

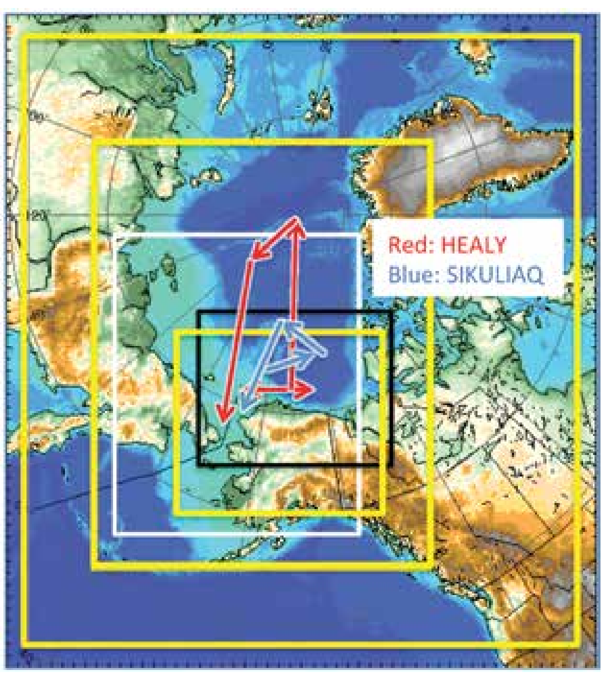

FIGURE 1
Yellow boxes: COAMPS nested domains (45 km, 15 km, 5 km). White box: CICE domain (5 km). Black box: WW3 domain. Arrows indicate (red) Healy and (blue) Sikuliaq areas of operations.

In support of these operations, and as part of the Regional Arctic Prediction component of the Earth System Prediction Capability, the U.S. Naval Research Laboratory (NRL) has developed the first regional, high-resolution, data assimilative Arctic modeling system. The modeling system is composed of NRL's Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS®), the Community Ice CodE (CICE) sea ice model, and the WAVEWATCH III® (WW3) wave model. The system assimilates atmosphere, ocean, and sea ice observations, and produces daily 72-hour model forecasts. The system output was utilized by the National/Naval Ice Center (NIC) and the USCG Research and Development Center to produce ice edge position and operational guidance.

Atmospheric Component: The atmospheric component of COAMPS is used to provide twice-daily 72-hour forecasts. The atmospheric forecast domain is configured to contain three nested grids with horizontal resolutions of 45 km, 15 km, and 5 km (Fig. 1, yellow boxes); each nest is configured with 60 vertical levels. An important COAMPS physics aspect relevant to the *Healy* missions is the newly implemented surface flux representation,[1] which is formulated based on the Surface Heat Budget of the Arctic Ocean (SHEBA) data to accurately model the surface heat and momentum fluxes between the air and sea ice. The initialization of COAMPS forecasts is performed by the Naval Research Laboratory Atmospheric Variational Data Assimilation System (NAVDAS) that analyzes observation soundings, surface, and satellite data, as well as previous 12-hour forecast fields. Lateral boundary conditions for the outermost (45 km) nest are provided by NAVGEM (Navy Global Environmental Model).

Sea Ice Component: The regional sea ice modeling is performed with CICE version 5.1.[2] CICE is run with 2 km horizontal resolution (Fig. 1, white box). The atmospheric forcing is obtained from the COAMPS 15 km domain noted above, while the ocean forcing and sea ice boundary conditions are obtained from the Global Ocean Forecast System (GOFS 3.1).[3] CICE inputs obtained from COAMPS include downward shortwave and longwave radiative fluxes, 2 m air temperature, and 10 m winds. CICE inputs obtained from GOFS include sea surface temperature, salinity, and currents. The regional CICE model assimilates satellite-derived ice concentration data from the Advanced Microwave Scanning Radiometer 2 (AMSR2) and Special Sensor Microwave Imager/Sounder (SSMI/S), and ice edge data from the NIC's Interactive Multisensor Snow and Ice Mapping System (IMS).

Wave Component: The regional wave modeling is performed with the WAVEWATCH III® wave model.[4]

WW3 is implemented on a 5 km horizontal resolution grid (Fig. 1, black box), and is forced with 10-meter atmospheric winds from the 15 km COAMPS forecasts. The wave model also imports ice concentration fields from the regional CICE model to incorporate the effects of sea ice on the waves. The scheme of Tolman[5] is used, with settings such that regions with concentration less than 25% and greater than 75% are treated as open water and land respectively, with partial blocking for intermediate concentrations. The regional WW3 grid uses directional wave spectra boundary forcing from a larger 16 km Pan-Arctic WW3 resolution[6] for the entire Arctic.

Operational Products: Each model output is sent to the NIC for sea ice location forecasts, and sent to the USCG for operational guidance. Since the Arctic is often bandwidth limited, graphical data for 40 model outputs are also generated and stored on an ftp site for retrieval by ship personnel. A sample of these graphical outputs is shown in Fig. 2. Figure 3 is a plot comparing modeled ice thickness and drift versus observed data obtained from the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) Ice Mass Balance Buoy (IMBB) program.[7] The drifts are within 2 cm/s. The thickness is within 0.2 meters except in the November time frame, when thick ice moved through the same model grid cell containing the IMBB. This system has successfully been run since June 2015, and will continue to be run through March 2016 in support of the Navy's Ice Exercise (ICEX) 2016 campaign.

[Sponsored by ONR]

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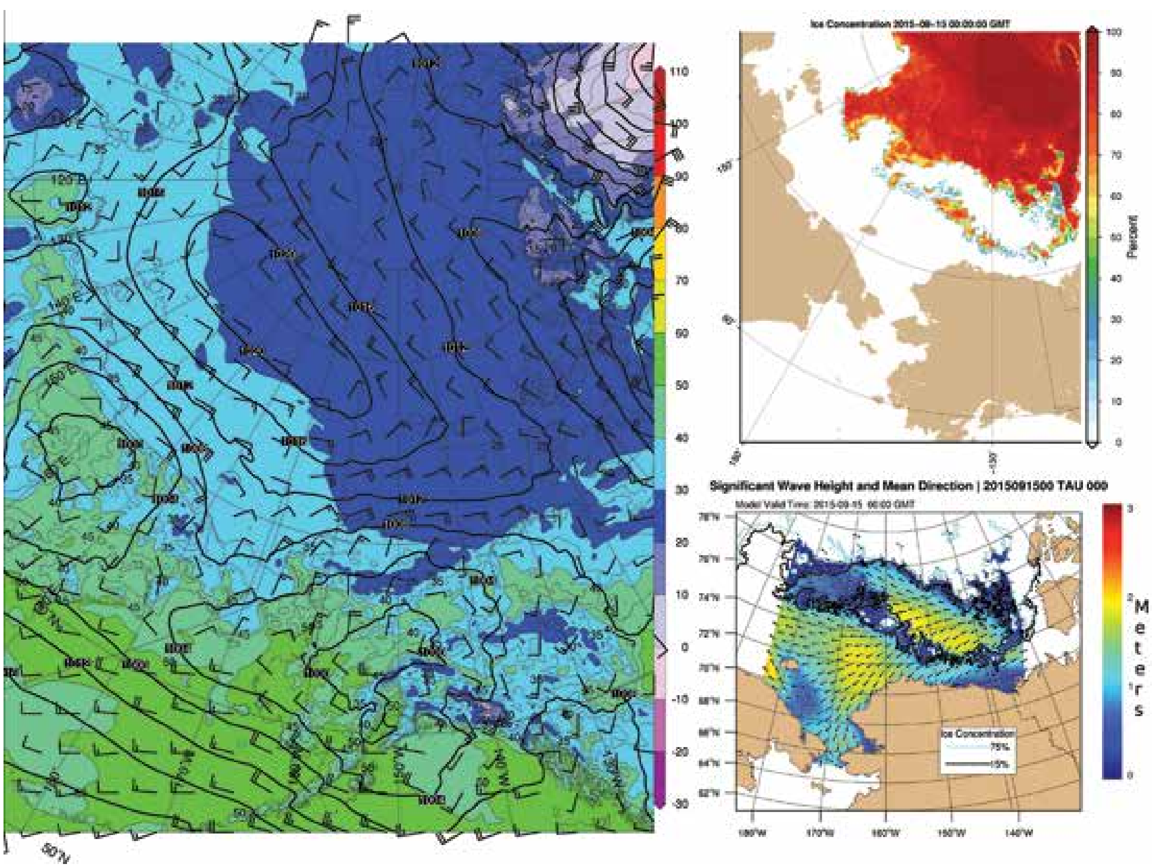

FIGURE 2

Sample output from the regional system on 15 September 2015. Left: COAMPS 2-m air temperature (color), sea level pressure (black contours), and wind barbs. Upper right: CICE sea ice concentration (percent coverage). Lower right: WW3 significant wave height (contour) and mean direction (arrows).

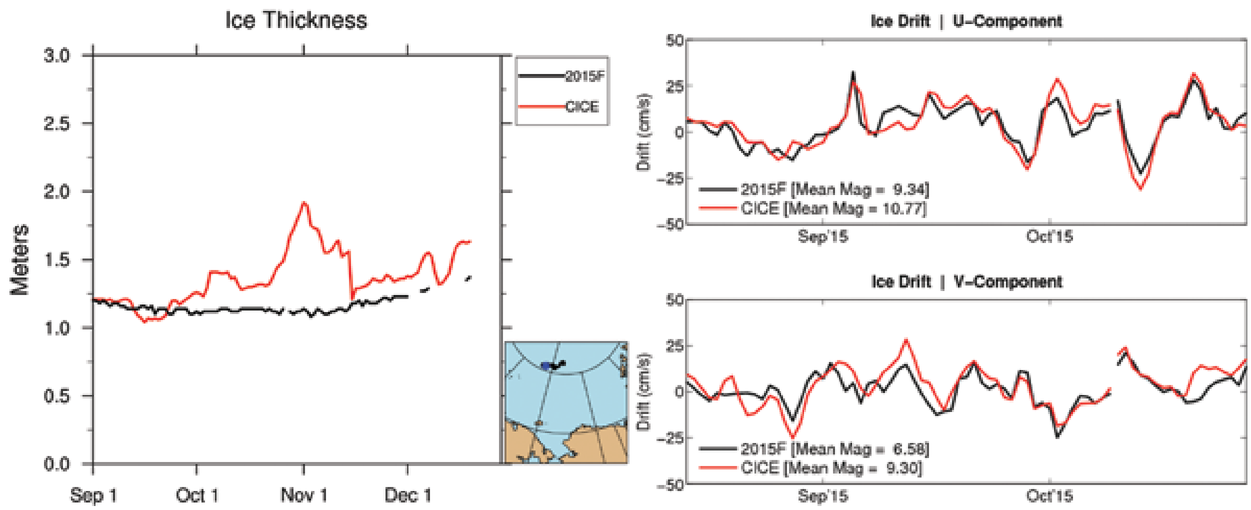

FIGURE 3
Comparison of (red) CICE modeled ice thickness and ice drift with (black) CRREL IMBB data (labeled 2015F).

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Multisensor Characterization of Marine Thin Layers

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Introduction: Marine ecosystems are sustained by the phytoplankton and zooplankton (primary and secondary producers, respectively) that comprise the base of the food web. Often, these organisms are found not at the water surface, but in high concentrations restricted to subsurface layers that are only tens of centimeters to meters thick, so-called "thin layers." Though thin, these layers may extend hundreds of meters to kilometers in the horizontal direction. They consist of particles and organisms that exist on much smaller scales of microns to millimeters. The ecophysiology, behavior, trophic interactions, and population dynamics of plankton are ultimately responsible for these layered phenomena. The biological nature of this community affects the entire ecosystem, potentially leading to healthy, productive fisheries or to unhealthy conditions caused by harmful algal blooms.

The U.S. Naval Research Laboratory (NRL) Ocean Sciences and Coastal and Ocean Remote Sensing branches, in collaboration with NOAA's Earth Systems Research Laboratory, conducted a series of joint field studies in East Sound, West Sound, and other nearby coastal waters of Orcas Island in the San Juan archipelago, off the northwest coast of Washington. The primary location, East Sound (Fig. 4), was chosen because it is a well-known environment for these "thin layer" phenomena.[1] The field studies utilized airborne, shipboard, and autonomous instrumentation to investigate the biological and bio-optical properties of the waters of the area.

Field Experiment: Thin subsurface layers were detected and characterized in East Sound using an array of instrumentation capable of spanning the relevant spatial scales. These layers were found and delineated using numerous sensors including airborne passive and active lidar (a laser-based radar analog),[2] ship-mounted lidar, a towed undulating vehicle, and bio-optical profiling instrumentation. For example, on 18 September 2013, airborne lidar detected a possible subsurface layer that appeared at 2 to 3 meters depth at the mouth of East Sound and gradually deepened to 5 to 7 meters near the head of the sound near the town of Eastsound to the north. At the same time, the research vessel *Humpback* progressed up the sound in a serpentine path, towing an undulating vehicle (Scanfish) equipped with physical and bio-optical sensors while simultaneously probing the water from the

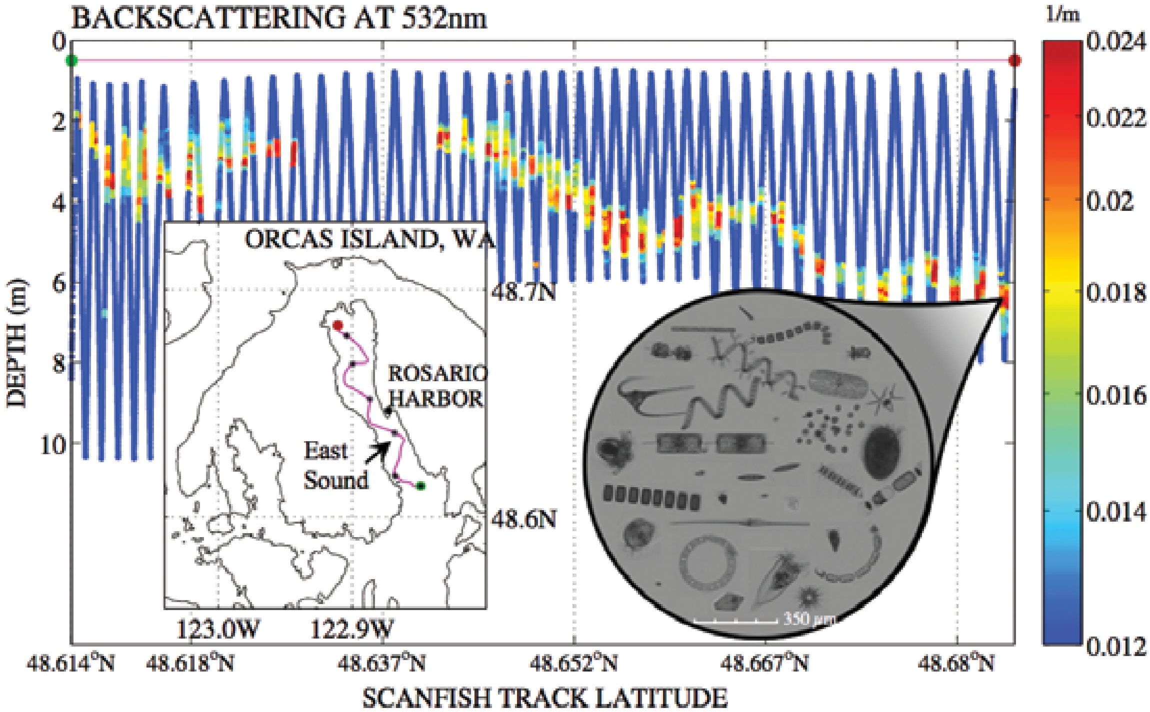

FIGURE 4

Subsurface "thin layer" (18 September 2013, East Sound) as seen via optical backscattering at 532 nm from a towed Scanfish platform (path shown by magenta line). Right inset: Examples of the plankton community within the "thin layer" at the end of the Scanfish transect. (Note: Most species images shown are from the 2015 deployment, as the imaging capabilities of the cytometer were upgraded between deployments.)

bow using the shipborne lidar. The ship-based survey confirmed the presence of a 1 to 2 meter thick layer which deepened from ~2 meters depth in the south to 6 to 7 meters in the north, with an east-west tilt (Fig. 4). Visible in both data sets is the interruption of the layer near Rosario Harbor by freshwater discharge from the Rosario Health Spa facility. At the end of the transect, an in situ sampling station was established to measure water column profiles and take water samples. Profiles of water temperature and salinity show sharp gradients (thermoclines and pycnoclines) that correspond to the depth of the thin layer. These "clines" are assumed to correspond to the nutricline and thus delineate the depth at which the phytoplankton obtain the optimum balance between light from the surface and nutrients from depth to allow the maximal rate of photosynthesis. With the sharp gradients in temperature, these clines represent regions of density and shear changes that can control the formation, extent, and breakup of the thin layers.

With a scanning, imaging, flow-cytometer, we measured profiles of total particle concentrations for the water column. Compared to the water above, in-layer concentrations were determined to be 3 to 5 times higher; the mean red fluorescence (a proxy for chlorophyll) of the particles was 4 to 6 times higher; and the average particle size was ~20% larger, with many more large (>100 µm) particles. Using the imaging capabilities of the cytometer (Fig. 4 inset) in conjunction with the fluorescent signal, we determined that the plankton community outside of the layer comprised small (<20 µm) flagellated phytoplankton and unhealthy large diatom chains. In contrast, the layer community contained many healthy, actively growing (seen in the process of cell division) chains of large diatoms and several species of dinoflagellates, both autotrophic and heterotrophic. In addition, the layers contained many zooplankton grazers from several classes: microflagellates, ciliates, copepods, and larvae of higher trophic level organisms.

Ominously, within the plankton assemblage, the harmful algal bloom (HAB)-forming organism *Alexandrium catenella* was found. This chain-forming, armored dinoflagellate species (Fig. 5) produces saxitoxin, the neurotoxin responsible for paralytic shellfish poisoning (PSP). Filter-feeding bivalve mollusks (mussels, clams, scallops, oysters) concentrate the PSP toxin in their tissues. Human consumption of contaminated animals (cooking does not remove the toxicity) can lead to severe sickness or even death. Fall 2013 saw many shellfish fishery closures in the Salish Sea area, which encompasses the study area, due to blooms of *A. catenella*.

During the subsequent East Sound field experiment in September 2015, thin layers were not detected

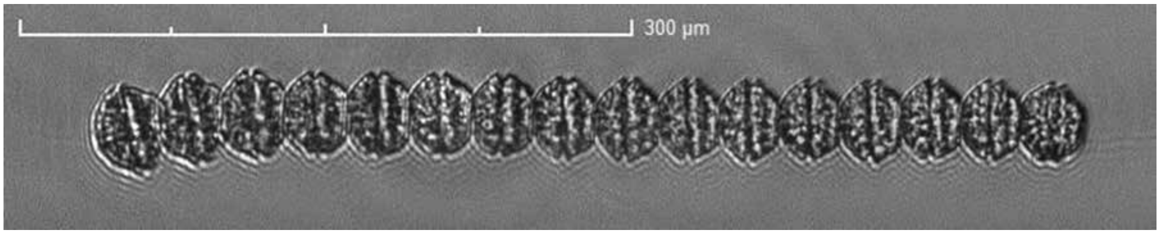

FIGURE 5
Chain of the HAB species *Alexandrium catenella* (dinoflagellate).

until the final day of the deployment. Instead, nutrient concentrations were found to be above the minimum threshold for phytoplankton growth throughout the water column (as determined by a newly acquired instrument, a submersible ultraviolet nitrate analyzer, SUNA). In the layers, we found healthy, dividing diatom chains of several species, but fewer dinoflagellates. As the cells in a diatom chain divide during normal, asexual reproduction, the cell size of each subsequent generation diminishes. At a certain point, contingent on environmental conditions (nutrients, temperature, and light), a sexual reproduction phase, auxospore formation, occurs which restores the normal, larger cell size. During this field experiment, we were able to image auxospore formation in one species of diatom, *Ditylum brightwellii*. The zooplankton grazer community was similar to the 2013 assemblage.

Significance: In addition to the ecological implications mentioned above, the presence or absence of layers in the water column has effects relevant to the performance of Navy electro-optical and acoustic systems. Equivalent vertically integrated plankton biomass concentrated in a thin layer will attenuate and reflect laser and acoustic signals differently. Also, many planktonic organisms, such as dinoflagellates and copepods, respond to disruptive stimuli with bioluminescent flashes; when this bioluminescence potential is concentrated in a thin layer, it has implications for several types of naval operations.

[Sponsored by the NRL Base Program (CNR funded)]

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Smarter Sampling of Seafloor Properties

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Introduction: Many characteristics of the vast and inaccessible seafloor are poorly resolved despite significant expenditure of funds and decades of direct observation by Navy, commercial, and academic interests. In remote regions like the Arctic and in politically denied areas, direct observations of seafloor properties are complicated, expensive, or otherwise impractical to obtain. Yet these observations are essential for understanding seafloor processes that directly impact the U.S. Navy. The U.S. Naval Research Laboratory Marine Geosciences Division (via the Carbon Flux Project) has recently developed a new approach to modeling key seafloor properties including temperature, porosity, and lithology at locations where observations do not exist. Here we describe the combination of readily available public data sets and machine learning techniques that allows us to link, for the first time, cross-disciplinary studies to predict global properties of interest. Our approach yields quantitative uncertainties and a guide (map) of locations where new observations would be most statistically helpful in global prediction. This is of particular importance for regions where direct sampling is exceptionally challenging. In the present example, we develop a global model of crustal heat flux.

Model: Our data-driven model, the Generic Earth Modeling System – Bayesian Network (GEMS-BN), uses machine learning to identify the conditional probabilities between crustal heat flux measurements and other known or modeled seafloor quantities. The analyses (here we used a Bayesian network, but other approaches can be substituted) allow heat flux estimates (with uncertainties) to be made at locations where no heat flux was observed. The resulting estimates significantly improve results over traditional gridding methods. Martin et al.[1] successfully applied a related approach to seafloor porosity. Ultimately, we will use these techniques to plan future direct measurements, which will minimize uncertainty in GEMS-BN.

The quantities included in GEMS-BN for heat flux were determined based on a sensitivity analysis. The conditional probabilities between the six most important variables were used to estimate crustal heat flux. The six variables are the following: the density of the Earth's mantle, which is the region between the Earth's crust and the Earth's core; the distance to the nearest mid-ocean ridge, the underwater mountain ranges where new seafloor is formed; the age of the seafloor; the number of nearby volcanoes; the elevation; the number of nearby active seamounts; and the density of the Earth's upper crust.

The conditional probabilities between variables in GEMS-BN allow us to estimate the probability of heat flux at a geographic location where heat flux is not measured, given the probability of the heat flux at other geographic locations with similar seafloor characteristics. For example, using GEMS-BN we can estimate the probability distribution of heat flux in an ice-covered region of the Arctic based on a geologically similar region in the Caribbean, which is much easier to sample.

Estimated Heat Flux: Global heat flux provides insights into the Earth's heat budget and internal dynamics,[2] as well as many other important geological processes such as the formation of gas hydrates,[3] changes to sediment properties,[4] and constraints on deep-biosphere life.[5,6] The integrated global heat loss from GEMS-BN is 31 TW, slightly lower than existing models for global heat flux. The spatial distribution of mean heat flux (Fig. 6) and standard deviation of heat flux (Fig. 7) reveal that heat flux is large and uncertain over mid-ocean ridges, where magma interacts directly with seawater. The model accurately represents high heat flux in the Red Sea and Pacific Ocean, where new crust forms, and accurately represents low heat flux in the Adriatic Sea and western Atlantic Ocean, where the Earth's crust is old and cool.

Smart Sampling: Perhaps the most important aspect of GEMS-BN is the ability to determine the most advantageous approach to making costly new observations. Our model estimates the *experience* (Fig. 8), which is the number of similar samples in variable space. Predictions with high experience are well constrained and have less uncertainty. Normalizing experience by area of the Earth's surface with similar seafloor characteristics allows us to determine, in variable space, where undersampling occurs, and where, geographically, new observations would best constrain our global heat flux model. For example, the red dots in Figs. 6–8 indicate a geologically similar region with an area of 5.36×10^5 km^2 that has no existing observations of heat flux. New observations in this region would be most effective at reducing uncertainty in global heat flux.

Implications: Our new seafloor properties model, GEMS-BN, uses a data-driven, statistically rigorous approach to estimate properties in locations where sampling is difficult or impossible. Our estimate of global heat flux, 31 TW, is slightly lower than previous estimates. Our model is an improvement on previous models in that we can quantitatively determine where new samples will prove most effective in reducing

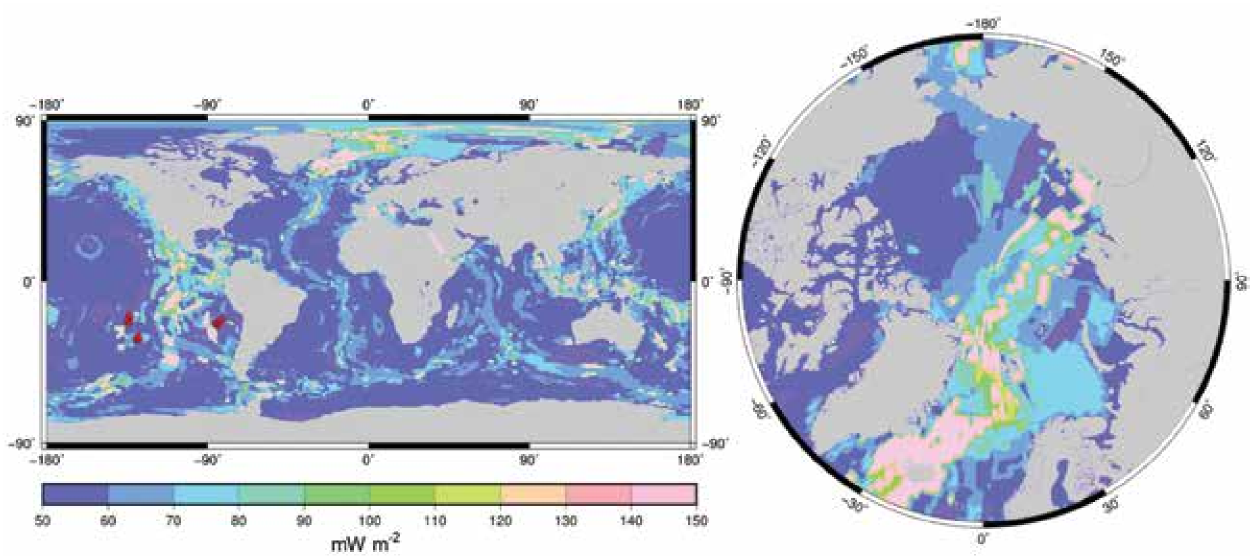

FIGURE 6
Global and polar projections of mean heat flux estimated with the GEMS-BN approach. Red dots indicate locations where new observations of heat flux would most improve our global estimate. Heat flux is important for understanding the global heat budget and internal earth dynamics as well as the formation of gas hydrates, changes to sediment properties, and deep-biosphere life.

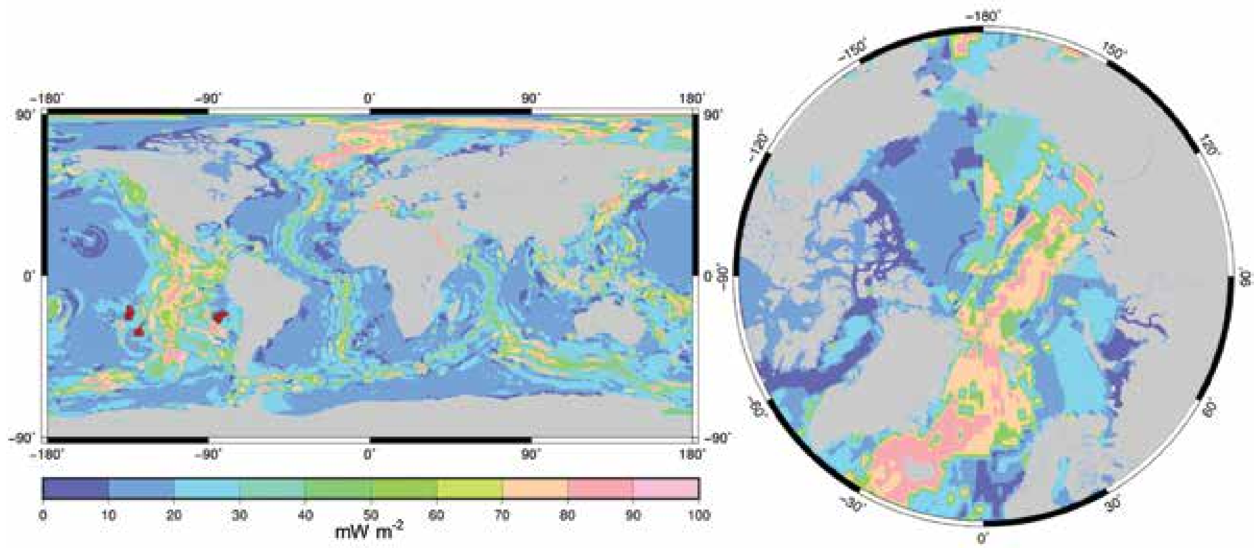

FIGURE 7
Global and polar projections of the standard deviation of heat flux estimated with the GEMS-BN approach. Uncertainty in heat flux is highest over mid-ocean ridge spreading centers, where magma directly interacts with seawater and fluxes can vary in magnitude over very short spatial scales.

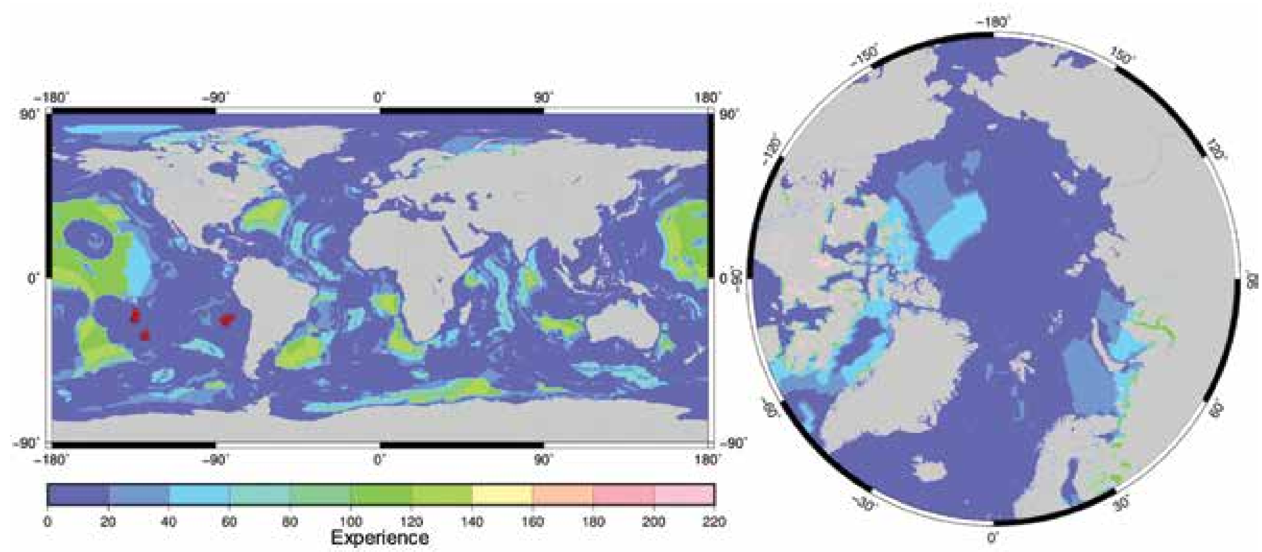

FIGURE 8
Model experience describes the number of heat flux observations that are geologically similar in GEMS-BN. Most regions of the global seafloor, including most of the Arctic, have no observations, indicating that more observations are necessary to constrain our estimates of heat flux. Using experience as a guide, we can locate the most effective areas to collect new samples (red dots).

model uncertainty. In the future, we will extend GEMS-BN to model other seafloor properties of interest to the Navy, including sediment grain size.

[Sponsored by the NRL Base Program (CNR funded)]

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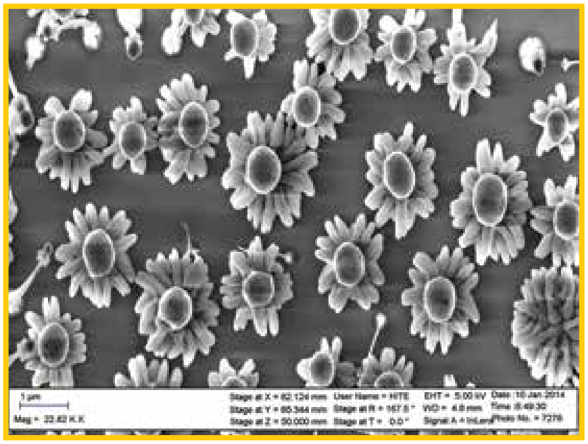
Optical Sciences

NRL SCIENCE AS ART CONTEST

Electronics Science & Technology Division Choice



Nanoworld Meadow

Nature creates beauty in unexpected ways, and this scanning electron microscope image proves just that. These hexagonal boron nitride (h-BN) crystals represent both aesthetic and chemical beauty. In an experiment to attempt growing h-BN platelet-like crystals vertically, i.e., oriented perpendicularly to a copper substrate, NRL researchers in the Electronics Science and Technology Division produced flowers instead of platelets, creating this distinctive looking nanoscale "meadow" of h-BN flower-like crystals. Research shows that h-BN has high mechanical strength and good thermal conductivity, as well as excellent chemical and thermal stability, making it a desirable dielectric substrate for high-performance graphene devices in optical positioning, remote sensing, and biomedical imaging.

Boris Feygelson and Jennifer Hite
Electronics Science and Technology Division

Common Airborne Situational Awareness (CASA) System

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Optical Sciences Division

Introduction: U.S. Naval Research Laboratory (NRL) scientists and engineers from the Optical Sciences Division designed, developed, and flight-demonstrated a lightweight podded system that provides continuous, long-duration, high-resolution video coverage of the entire airspace around a host aircraft. Designated the Common Airborne Situational Awareness (CASA) system, the project was completed within an 8 month time window and provides continuous forensic video in the very demanding environments encountered by U.S. Navy Maritime Patrol and Reconnaissance Aircraft (MPRA). The CASA system was installed and flight tested on an NRL P-3 research aircraft flown by Scientific Development Squadron ONE (VXS-1). The system autonomously monitored and recorded intercept maneuvers of District of Columbia Air National Guard F-16 and Hawaii Air National Guard F-22 aircraft as they engaged the NRL P-3 aircraft in simulated intercept activities.

System Details: The CASA pod consists of five high-dynamic-range, high-resolution video cameras and high-speed storage and video processing to provide real-time airborne situational awareness. It operates over the entire flight envelope of air speeds and altitudes of MPRA aircraft, withstanding the temperature and vibration environments without performance degradation. The imaging performance requirements include recording color video over illumination conditions that can vary by several orders of magnitude, successfully alternating from imaging aircraft backlit with direct sunlight in the frame to imaging aircraft framed by bright white sunlit clouds. Additional performance requirements include imaging resolution sufficient to read identifying target-aircraft alphanumeric markings at typical intercept ranges. Among CASA's features are a design based on the standard ALQ-167 pod structure; rugged 12 Mpixel commercial off-the-shelf cameras with a minimum of 10 bits of dynamic range; and a rugged vibration isolation mount for the lenses and cameras within a custom-sealed, pressurized enclosure with an abrasion-resistant, domed ALON window (transparent ceramic, Surmet Corp.). Figure 1 shows system details.

The CASA program also designed and implemented the real-time, autonomous dynamic exposure and color balancing processing algorithms required to enable imaging operations over this demanding range of environments. CASA video compression enables the storage, retrieval, and search of the high-resolution video over the duration of an entire 12-hour mission and gives an in-cabin operator the capability to extract high-resolution data in real time. Exploited imagery and video can be transmitted to ground personnel before the completion of flight mission activities (see Fig. 2).

The design of the CASA pod system is based on modularity, with the ability to support multiple host aircraft and imaging payloads. The ALQ-167 base structure has been flight certified on several aircraft in the U.S. Navy inventory. The imaging packages are individually removable, allowing for the rapid replacement of cameras or the rapid change of imaging band (EO/IR/UV). In addition, the entire nose and tail sensor payload sections of the pod are removable, enabling new advanced sensor payload packages to be rapidly inserted and deployed. Example payload packages include signals intelligence (SIGINT), hyperspectral imaging (HSI), light detection and ranging (LIDAR), synthetic aperture radar (SAR), infrared search and track (IRST), and infrared countermeasures (IRCM).

Flight Testing: The first demonstration flight series of the CASA pod on an NRL P-3 was conducted over the course of one week, culminating in several mock foreign aircraft intercepts by two District of Columbia Air National Guard F-16s, the squadron tasked with all intercept activities in the National Capital Region airspace. Initial CASA flights verified flight operation at altitudes up to 23,000 ft, operation in heavy rain and high heat, CASA image quality, and use of CASA imagery to accurately measure distance to approaching aircraft. Imagery was obtained with the sun in the field of view and under dark, pre-sunrise lighting conditions. Exploited imagery/video was analyzed on board with the in-cabin exploitation system.

After the success of the initial Washington, DC area flight test series, CASA deployed to Hawaii in mid-July 2015 for demonstrations to Pacific Fleet leadership and Patrol and Reconnaissance Wing TWO and Patrol Squadron FOUR operators. This sequence of test flights, conducted in conjunction with Hawaii's Air National Guard F-22s, further highlighted the system's inherent simplicity and ability to capture high-resolution dynamic maneuvers around the aircraft without requiring crew intervention. Intercept maneuvers were recorded at many ranges, closing speeds, and aspect angles relative to the P-3, demonstrating imagery handoff between overlapping sensor views during very dynamic flight maneuvers (see Fig. 3).

The CASA pod flight tests demonstrated that the system can provide an irrefutable video record of ad-

FIGURE 1
CASA host aircraft situational awareness coverage; CASA pod installation on NRL VXS-1 P-3; internal pod layout showing main components; camera sealed ruggedized can assembly; and imagery exploitation viewing capability.

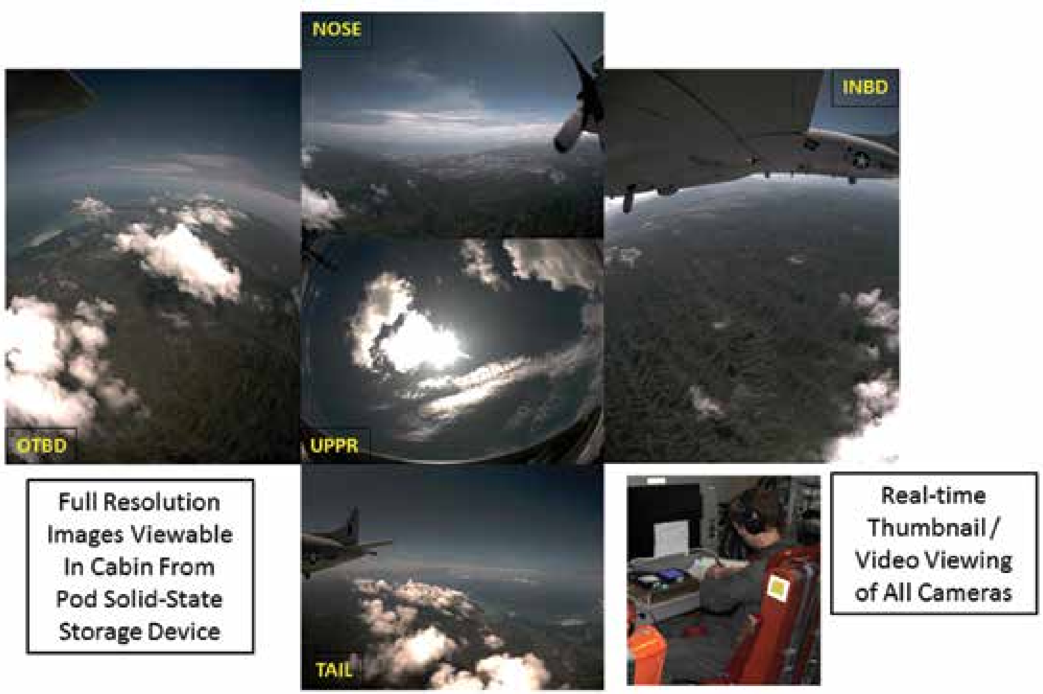

FIGURE 2
In-cabin exploitation station allows for real-time exploitation and secondary dissemination of video products. The five camera views shown are from the July 2015 Hawaii flight test and include overlapping nose, upper, tail, outboard, and inboard sectors. All camera fields of view include a portion of the host aircraft to allow for mensuration and positive situational awareness identification.

versary aircraft actions that interfere with the conduct of missions by U.S. Navy MPRA. It also provides general situational awareness of the entire airspace around a host aircraft, complementing other MPRA sensors. The CASA pod modular system design will allow for rapid flight testing and deployment of future advanced sensor technologies on several U.S. Navy aircraft types.

FIGURE 3
CASA image segment showing inboard camera view of F-22 intercepting the NRL P-3. Image resolution of actual imagery is sufficient to easily identify and read the interceptor's tail number.

Acknowledgments Special thanks to the NRL VXS-1 team, USAF Air National Guard (113th Wing and 199th Fighter Squadron), U.S. Navy Patrol and Reconnaissance Wing TWO and Patrol Squadron FOUR, Alaire, Inc. (D. Thornburg, J. Schlupf, R. York), Space Dynamics Laboratory (Z. Butikofer, C. Meadows, B. Petersen, D. Miller, D. Hansen, K. Reese), Smart Logic, Inc. (M. Colbert, C. Colbert, S. Frawley, B. Mathieu, R. Sagusti), Platform Systems (C. Essington, S. Yarosh, D. Fluker), and DCS, Inc. (M. Kruer).

[Sponsored by the NRL Base Program (CNR funded)]

Antireflective Surface Structures on Laser Optics

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Introduction: The optics in kilowatt-class high energy laser systems operating near 1 µm require antireflective surfaces to mitigate Fresnel reflections associated with the refractive index difference between air and the optics. For example, a silica glass window has 7% total reflection loss, producing undesirable effects including reduced optical power transmission, stray reflections, and feedback into the laser system. These reflections are traditionally mitigated by applying thin film dielectric stacks of materials that are designed to behave as antireflective (AR) coatings for the desired wavelength range. However, since these coatings consist of foreign materials deposited on the optical surface, they have serious shortcomings, including susceptibility to delamination under thermal cycling due to thermal expansion mismatch between the coating and substrate, and higher susceptibility to laser-induced damage as compared to the substrate. Another disadvantage is that by design, the AR coatings perform well for only a limited optical bandwidth and angular range.

An attractive alternative to AR coatings is the use of novel antireflective surface structures (ARSS), which are microstructured patterns etched in the optical surface.[1] The technology mimics nature in that there are submicron features on the surface of a moth's eye that reduce visible reflections and enhance their night vision. State-of-the-art processing has resulted in antireflective performance of ARSS on optics that is comparable to that of traditional AR coatings. However, unlike the coatings, these structures are not deposited but instead are directly etched into the surface of the optic, so that delamination effects are eliminated.

Design and Fabrication: ARSS on an optical surface may be understood conceptually as providing a gradual transition in refractive index from air to the optical substrate. The ARSS consist of arrays of nanoscale structures in which the period of the pattern is designed to be on a subwavelength scale so as to avoid undesired diffraction effects, while the height of the individual features is on the order of one-half the wavelength. The specific size and shape of the structures are modeled computationally for the particular material and wavelength region using methods such as finite element analysis or effective medium theory. The ARSS may have an ordered, repeating pattern (Fig. 4, left), typically fabricated using a lithographic process followed by dry or wet chemical etching. Alternatively, a nonperiodic array of structures of varying height and spacing, often called "random ARSS" (Fig. 4, right), can

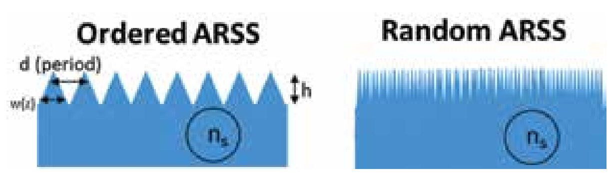

FIGURE 4
Schematic cross section of an optical surface with index n_s for ordered ARSS (left) and random ARSS (right) where for low reflectance at wavelength λ, the features have height >λ/2 and spacing $d < \lambda/(2n_s)$.

be created on the optical surface by using a reactive ion etching process, using gases that are chemically reactive with the optical surface.

Optical Performance: The U.S. Naval Research Laboratory has advanced the utility of ARSS fabrication on silica windows and lenses, which are widely used for high energy lasers in the 1 µm region. The surface reflectance for these silica windows with ARSS has been reduced to a record low 0.02% at 1.06 µm, rivaling the performance of high-quality AR coatings. Figures 5(a) and (b) show scanning electron microscope images of the surface features in random ARSS on silica glass. Tests on these samples using a 10 ns pulsed laser at 1.06 µm show a record high laser damage threshold of 100 J/cm^2, which is not only comparable to that for the untreated surface, but is 5 times higher than that for a window with a traditional AR coating. The random ARSS are also suitable for highly curved or conformal optics, as demonstrated with ARSS fabrication on 5 mm hemispherical lenses that show 0.4% residual surface reflections, nearly an order of magnitude lower than for an untreated lens.

A key feature of the ARSS is the broadband transmission. As illustrated in Fig. 6, a window with dual-sided ARSS shows transmission increase to 99.5% in the wavelength range from 775 to 1350 nm, which is a significantly wider range than for typical AR coatings. The random ARSS fabrication is also highly suitable for scale-up, depending only on the size of the etching chamber. Transmission of a hexagonal silica glass window with maximum linear dimension of 33 cm and ARSS on one side is as high as 95.6% at 1.06 µm, which is 99% of the theoretical maximum value, with excellent uniformity over the surface. ARSS fabrication is thus highly attractive for the actual sizes of windows needed for high energy laser systems that range from 30 to 50 cm. Finally, ARSS fabrication can also be applied to the end faces of 125 µm diameter single mode silica fibers, yielding increased surface transmission of 99.4% at 1550 nm and a high laser damage threshold comparable to that for untreated fibers, thus impacting the practical application of fiber lasers that are becoming increasingly important as high energy laser sources.

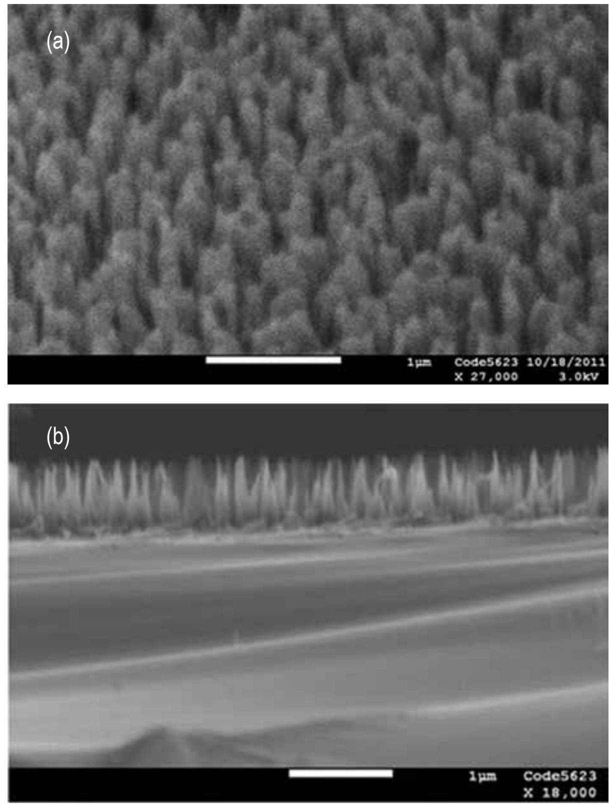

FIGURE 5
Scanning electron microscopy images of the surface of silica with random ARSS, where (a) shows the top view and (b) shows a cross-sectional view along a cleaved edge of the sample. The scale bar corresponds to 1 µm and depth of the surface features is 400 nm.

Summary: We have advanced the technology for fabrication of AR surface structures on different optics

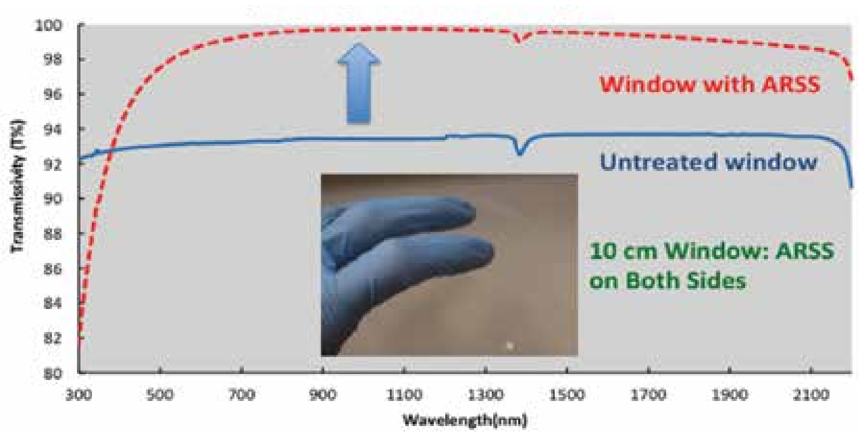

FIGURE 6
Transmissivity through a 10 cm silica window with ARSS on both sides (red curve) as compared to an untreated window (blue curve). Inset photograph shows the sample tested.

only significantly decreased reflectance, but also very high laser power handling capability for windows, lenses, and fibers. This successful utility of ARSS on optics is a game-changing technology with direct impact on the practicality of high energy laser weapons systems.

Acknowledgments: We acknowledge the fabrication of ARSS on samples by TelAztec, Inc. and the University of North Carolina, Charlotte.

[Sponsored by the Joint Technology Office for High Energy Lasers]

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Highly Accurate Refractive Index Measurements for Thin Samples

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Introduction: Optical imaging systems strive to achieve perfect focusing as efficiently as possible. For high-quality optics, control of both the lens shape and lens material is critical. It is not uncommon to specify the refractive index of optical glasses out to at least four decimal places. Improving image quality with fewer lens elements can be done with gradient index (GRIN) optics, which places an even greater importance on refractive index metrology. GRIN lenses have internal material variations which bend light both at the surfaces and in color-dependent ways throughout the lens medium. Properly designed, single GRIN lenses can replace two or more conventional lens elements. GRIN optics has gained recent attention due to the development of a new material system incorporating 50-micron-thick nanolayered polymer films, each extruded with a different, well-controlled index value.[1] To support the fabrication of high-quality GRIN optics, the U.S. Naval Research Laboratory (NRL) Optical Sciences Division developed an accurate means of measuring refractive index in polymer films. NRL validated the technique by measuring refractive indices accurate to $<3 \times 10^{-5}$ in several glass samples,[2] and reported new results for a film of poly(methyl methacrylate) (PMMA) for wavelengths from 0.4 to 1.6 microns.[3] This method can be extended to other materials and wavelength bands, provided a suitably accurate spectrometer, suitably thin samples with near-parallel faces, and an independent means of acquiring refractive index measurements at two or more wavelengths.

Background: The most accurate means of measuring refractive index relies on the deflection of light through precisely fabricated prisms. However, such a prism cannot be made from a single polymer film. A prism-coupled refractometer can make accurate refractive index measurements of a polymer film, but only at individual laser wavelengths. Given the cost and complexity of incorporating multiple lasers into a setup, it is uncommon to achieve more than 10 independent index measurements in this way. NRL developed a means by which four such index measurements can be combined with a rapidly acquired transmission spectrum (30 seconds or less) to generate hundreds of equally accurate index measurements across a broad spectral bandwidth.

Method: The transmission spectrum of light through a thin film exhibits a series of peaks and valleys — as seen in the rainbow of colors on a soap bubble. The goal of this work was to transform the peak wavelength locations into accurate measurements of material refractive index. A transmission peak occurs where the round-trip thickness of the material, twice the sample thickness D, is an exact multiple M of the optical wavelength within the material $[\lambda_{vac} / n(\lambda_{vac})]$, where λ_{vac} is the wavelength in vacuum and $n(\lambda_{vac})$ is the corresponding index of refraction. The spectrum provides accurate measurements of the index

$$n(\lambda_j) = M_j \lambda_j / (2D)$$
$$\{\text{for all transmission peak wavelengths } \lambda_j\}$$

at each peak wavelength λ_j when D, λ_j, and the integer peak number M_j are all identified accurately.

It is the measurement of D that typically hampers the fidelity of this technique. To achieve four digits of accuracy in $n(\lambda_j)$, at least that level of thickness accuracy is needed, too. For our polymer samples, thickness variations across the films fall well short of that precision. Therefore, NRL performed independent, accurate measurements of the index at several wavelengths. By knowing the wavelengths at which the index measurements were made, and their locations with respect to the peak numbers M_j in the spectra, we could accurately estimate D … straight from the transmission spectrum. With a known thickness, all peak wavelengths can be turned into accurate index measurements (Fig. 7).

Results: We had to address many sources of error in order to achieve an absolute measurement with five

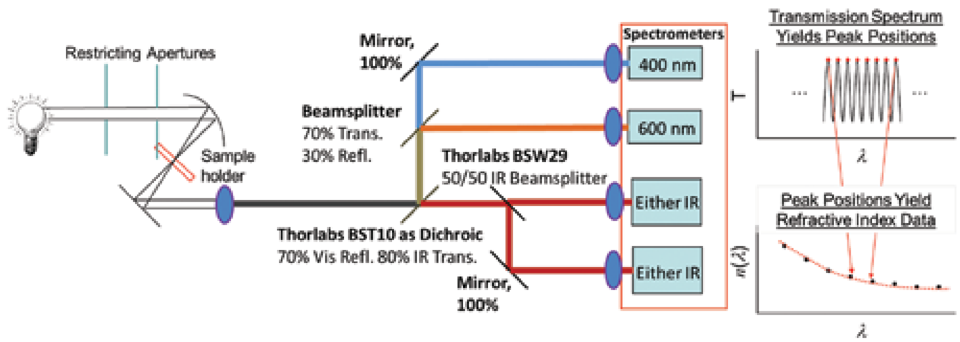

FIGURE 7
NRL's fringe spectrometer. White light transmitted through a thin sample is coupled into four static-grating, high-resolution spectrometers by dichroic beam splitters and mirrors. Wavelength coverage 0.40–1.64 mm. (See Ref. 2.)

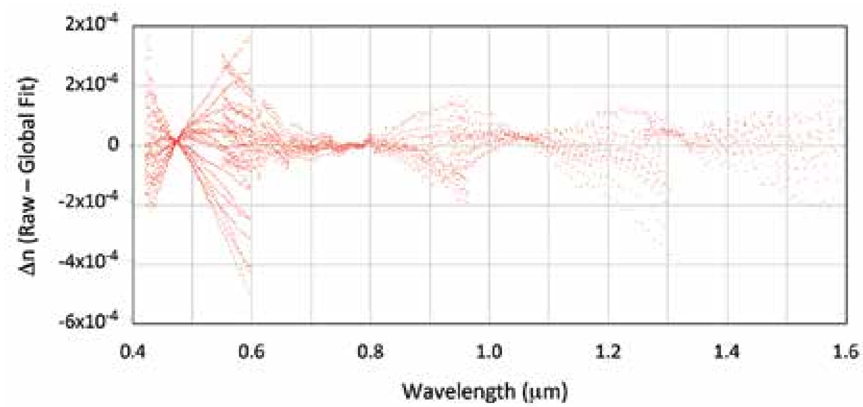

FIGURE 8
Plot of PMMA fit residuals for the full set of 16 measurement locations. The plot contains a total of 4565 data points. "Raw" refers to the measured value. (See Ref. 3.)

digits of accuracy. Reference 2 provides the details of our setup, including the development of a new method we used to calibrate our spectrometers. We validated the technique by measuring the refractive index of known glasses with rms accuracies <3 × 10^{-5} at more than 200 wavelengths between 415 nm and 1610 nm. In a more recent paper,[3] we present measurements of PMMA. As pointed out in Ref. 2, the largest residual uncertainty in refractive index is due to uneven sample surfaces. To alleviate this issue, measurements were made at 16 different locations across the PMMA sample, resulting in a dataset containing peaks measured at more than 3000 independent wavelengths between 420 nm and 1620 nm (Fig. 8). Our fit through these points resulted in a dispersion curve with an estimated rms uncertainty <5 × 10^{-5}. We identified an additional wavelength-independent uncertainty of ±1.8 × 10^{-4}, specific to the PMMA, which affects the vertical position of the curve on an n versus λ plot but not the accuracy of its shape or dispersion.

Summary: NRL developed a method for highly accurate refractive index measurements suitable for thin, transparent samples. It combines two or more discrete index measurements with a broadband transmission spectrum to obtain index values across the spectral bandwidth. Validated with known glass samples, the method was used to measure $n(\lambda)$ for PMMA. Those data represent an order of magnitude improvement in accuracy and 2 orders of magnitude improvement in the number of wavelengths measured over any previous measurement of PMMA.

[Sponsored by the the NRL Base Program (CNR funded)]

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NRL SCIENCE AS ART CONTEST

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Flexible BioElectronics as "Plants"

This photo-collage of NRL work on flexible bioelectronics showcases how NRL researchers in the Center for Bio/Molecular Science and Engineering can create sensing and biomimetic electronics in arbitrary and interesting patterns, such as pictures of plants. The "leaves" in the collage are actually sweat sensing tags that can be placed on the skin. The "flowers" actually started out as flat sheets and self-folded into three-dimensional spiral structures. All the leaves and flowers were formed from extremely thin nano-cellulose, which was then cut into the desired shapes and laminated onto a patterned silicon wafer. The devices were printed with a fluorescent ink that enables them to glow under black light.

Jonathan Yuen
Center for Bio/Molecular Science & Engineering

Bistatic ISAR for Teamed Aircraft Imaging

R.D. Lipps and R.G. Raj
Radar Division

Introduction: Inverse synthetic aperture radar (ISAR) imaging uses the rotational motion of objects to form two-dimensional, high-resolution images that can aid in the identification of objects of interest in all weather conditions. Currently, only monostatic ISAR imaging systems are used operationally. Monostatic systems have collocated transmitters and receivers and have limitations in maritime ISAR applications due to poor target aspect, low monostatic radar cross section (RCS), and short operating ranges. Operating range is limited by signal propagation loss, which is inversely proportional to the fourth power of the distance separating the target and the monostatic radar. Surveillance aircraft operating a monostatic ISAR radar are at risk because they must maneuver close enough to the surveillance area to detect and image targets.

A bistatic radar system uses a non-collocated transmitter and receiver(s) that provide greater aspect diversity than does a monostatic ISAR system. This results in more consistent image resolution. For example, observing a ship at broadside is the worst-case aspect for monostatic ISAR imaging because there is limited target range extent at that angle. However, when a bistatic receiver is located at an aspect that is 90° from the transmitter relative to the target, the image resolution of the ISAR improves; Fig. 1 illustrates this example. A bistatic system also allows greater transmitter standoff ranges. A forward deployed receiver, such as on an unmanned air vehicle (UAV), is used to compensate for the longer transmit path by shortening the receive path.

Bistatic ISAR Image Processing: The added capability offered by bistatic ISAR comes at a cost of having to synchronize receive data with the non-collocated asynchronous transmitter. Asynchronous operation poses a challenge for the coherent processing necessary to form ISAR images. A further challenge is that the paths from the transmitter, receiver, and target change due to the motions of the platforms, and this increases the complexity of the target translational motion. Translational motion between the radar and the target results in range shifts and phase modulation in the received signal, causing the ISAR image to defocus.

The U.S. Naval Research Laboratory has developed a novel bistatic ISAR imaging process that combines techniques for transmit-receive synchronization and robust motion compensation. The direct path signal between the transmitter and receiver is used to synchronize the received signal with the transmitted waveform. This direct path signal provides the timing baseline and the reference phase for the coherent processing of each radar pulse. A polynomial motion model is used to estimate the target's translational motion and the polynomial coefficients are determined using a measurement of the pulse-to-pulse range shift and an estimate of phase errors. The model is used to compensate for the translational motion, allowing standard monostatic ISAR techniques to form the image. Figure 2 is a flow diagram for the bistatic ISAR processing.

Simulation Results and Summary: We demonstrate the effectiveness of the bistatic ISAR technique using synthetic ISAR phase history data and then

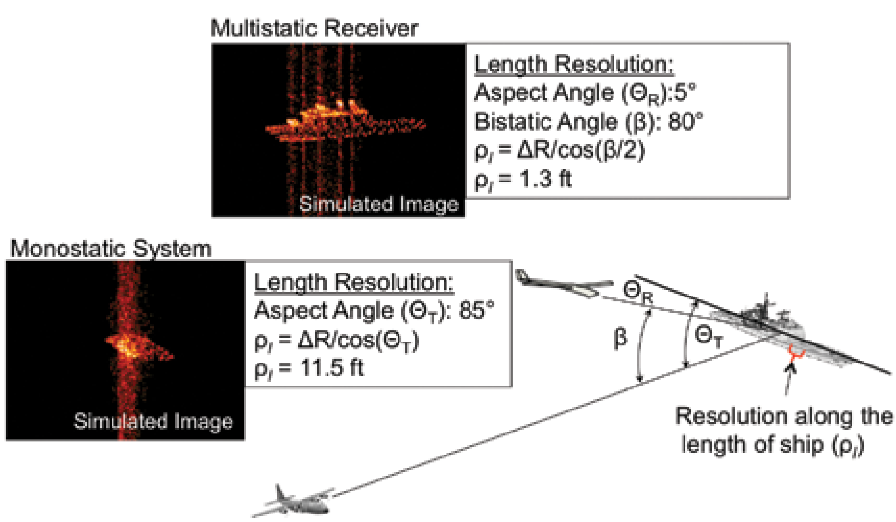

FIGURE 1
Example of the image improvement from a bistatic receiver for an unfavorable monostatic aspect angle.

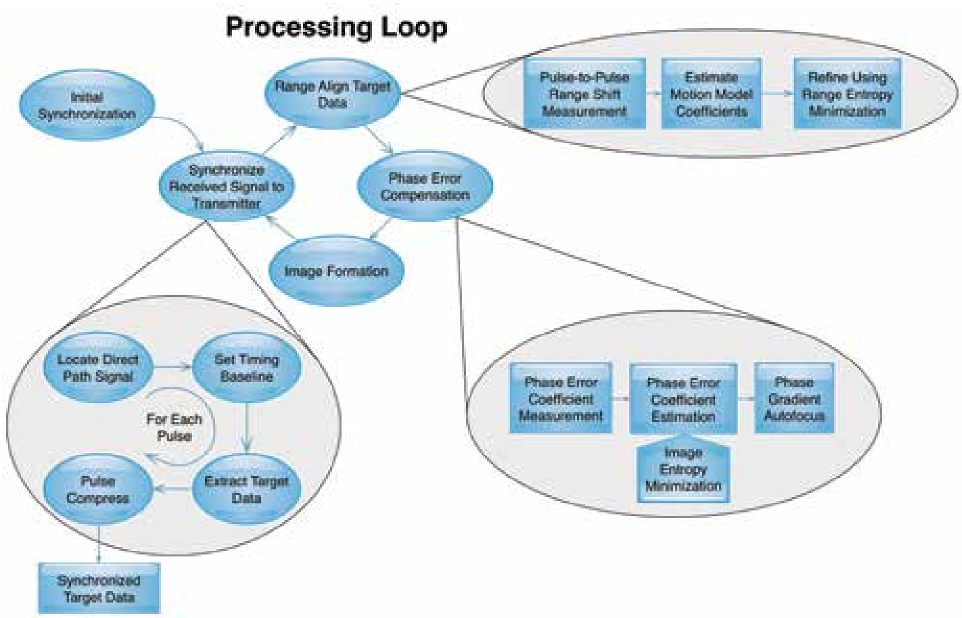

FIGURE 2
Top-level flow diagram of the bistatic ISAR imaging process.

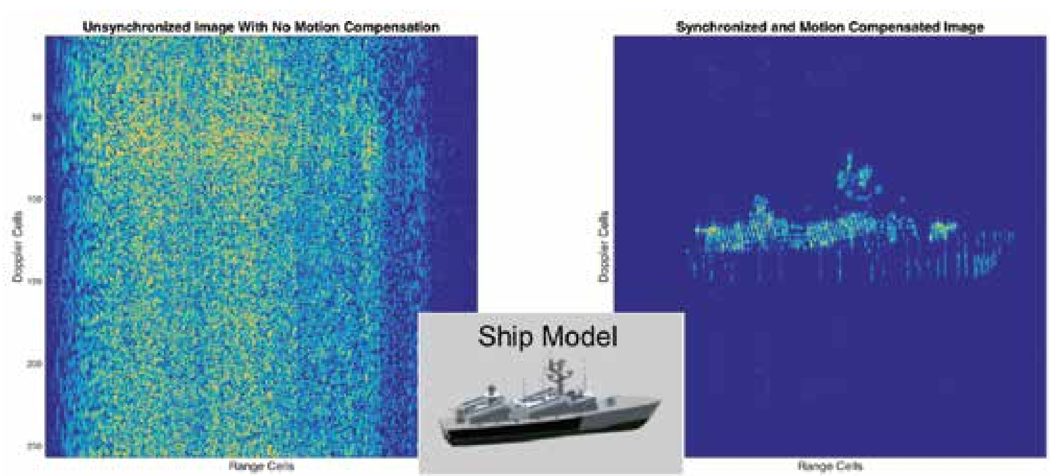

FIGURE 3
Comparison of simulated data without (left side) and with (right side) the bistatic synchronization and motion compensation.

processing it with and without the bistatic ISAR imaging technique. For this example, the transmitter moves away from the target at a velocity of 60 m/s and the receiver moves perpendicular to the target at 30 m/s. A fourth-order polynomial is used to model the target's translational motion and a sinusoidal model is used for the target's rotational motion. Figure 3 shows the significant improvement in ISAR image quality when bistatic ISAR techniques are applied to a single image from the example data sequence. The left side image is the result using the standard ISAR technique and the image appears as noise. The right side image is the result using the bistatic ISAR technique and the target is clearly discernible.

NRL's new bistatic ISAR image processing technique can be employed using existing fleet maritime surveillance assets. A radar on a manned aircraft or helicopter could serve as the bistatic transmitter, and an appropriate receiver on a small UAV would provide the bistatic receiver(s). In this concept of operations, the UAV is forward deployed in a hostile area and the manned aircraft operates at a safe standoff range.

[Sponsored by the NRL Base Program (CNR funded)]

The NRL/NASA Middle Atmosphere Microwave Network

R.M. Gomez and G.E. Nedoluha
Remote Sensing Division

Monitoring the Middle Atmosphere: The U.S. Naval Research Laboratory (NRL) operates a network of eight ground-based microwave instruments for measurements of the middle atmosphere, which encompasses the stratosphere (~15–50 km above the surface) and the mesosphere (~50–80 km above the surface). The network measures ozone (O_3), water vapor (H_2O), and chlorine monoxide (ClO). This NASA-sponsored activity, led by an NRL principal investigator, combines what since 1990 had been three separate projects, in which NRL had provided the H_2O measurements, the University of Massachusetts the O_3 measurements, and the State University of New York (SUNY) at Stony Brook the ClO measurements. These three projects were founding members of the Network for the Detection of Atmospheric Composition Change (NDACC), an international consortium of high-quality instruments dedicated to assessing the impact of stratospheric changes on the underlying troposphere and on global climate.

NASA, as well as the previous principal investigators of these projects, recognized that only NRL had the necessary expertise (as demonstrated by the replacement of its H_2O instruments over the last decade) to maintain and replace the aging O_3 and ClO instruments, and thereby to ensure that these valuable datasets could be extended. As a result, NRL now operates an H_2O instrument at Table Mountain, California; O_3, ClO, and two H_2O instruments at Mauna Loa, Hawaii; O_3 and H_2O instruments in Lauder, New Zealand; and a ClO instrument at Scott Base, Antarctica. Figures 4 and 5 show the Mauna Loa site.

FIGURE 4
The microwave hut at Mauna Loa. A feedhorn antenna from the WVMS6 instrument looks out the window at a movable mirror which directs the measurement beam. A reference target is above the mirror.

FIGURE 5
A look inside the Mauna Loa microwave hut. The instrument in the foreground is MOPI3, behind it is ChlOE4, and at the back is WVMS5. WVMS6 is out of frame to the left.

The microwave instruments measure the thermally excited emission line near 22 GHz (H_2O), 110 GHz (O_3), and 278 GHz (ClO). The spectrometer bandwidth permits measurement of the pressure-broadened lineshape from which altitude profiles are retrieved. Ideally, the instruments are positioned at high-altitude, low-moisture sites such as Mauna Loa and Table Mountain. The New Zealand site provides Southern Hemisphere measurements for comparison, while the measurements of ClO in Antarctica are key to understanding the ozone hole, since ClO is both the direct product of the reaction between Cl and ozone and the catalytic agent in the most important ozone-depleting chemical cycle.

Instrument Upgrades: When the instruments were deployed in the 1990s, they were state of the art. However, advances in thermal noise cancellation and reduction techniques, combined with microscale and nanoscale manufacturing techniques, now enable us to field instruments with more capability and better stability. In particular, the development of the field-programmable gate array (FPGA) has produced digitizers capable of real-time fast Fourier transform (FFT) analysis which now allows us to replace the ~100-channel filter banks with 16,000-channel spectrometers, while at the same time reducing power consumption and instrument size and improving accuracy and stability.

These advances have been deployed in all four Water Vapor Millimeter-wave Spectrometer (WVMS) instruments, two new Chlorine monOxide Experiment (ChlOE) instruments, and one new Microwave Ozone Profiling Instrument (MOPI), all designed and built by NRL. An additional MOPI instrument is currently in the design phase. Transitioning between old and new technologies requires a major redesign of the systems. However, preserving the stability and integrity of the long-term data record is paramount.

Long-Term Global Data Trends: Because these instruments have been operating nearly continuously since the 1990s, they provide important data for addressing key scientific questions: (1) Is ClO declining as expected due to the decrease in anthropogenic chlorofluorocarbon (CFC) emissions? (2) Is stratospheric O_3 recovering due to this decrease in CFC emissions, and is this decrease consistent with the ClO changes? (3) Is stratospheric H_2O changing, and to what extent can variations in surface temperature be attributed to these changes? An important feature of measurements in the middle atmosphere is that measurements from just one or two sites can provide a good measure of global trends in these species.

We have measured decreases in ClO since the mid-1990s at both the Hawaii and Antarctica sites. Both ground-based datasets show decreases in ClO of ~0.6% yr^{-1}. This is consistent with the decrease in CFC emissions that has resulted from the implementation of the Montreal Protocol, which was agreed to in 1987 after the discovery of the ozone hole.

Ozone had been decreasing in the upper stratosphere in the early 1990s, but since the late 1990s there is the hint of a positive trend (~0.2% yr^{-1}). A number of satellite instruments measure ozone trends, but these measurements are difficult to merge because upper stratospheric ozone undergoes a diurnal variation, with higher ozone levels at night. One of the most important contributions of the ground-based microwave measurements is that they measure 24 hours per day, and hence can provide the diurnal variation information required to merge data from satellite measurements, which are generally made at different local times.

Unlike ClO, which is currently decreasing, and O_3, which is thought to be slowly increasing (both because of the change in CFC emissions), it is not clear whether changing anthropogenic inputs over decadal scales will lead to an increase or a decrease in H_2O in the middle atmosphere. Measurements from Mauna Loa since 1996 show almost no net change over the past 20 years (<0.1% yr-1), but there are shorter multi-year periods during which upper stratospheric H_2O changed significantly. As an example, following the eruption of Mount Pinatubo in the early 1990's we observed a large increase in upper stratospheric H_2O. Understanding changes in H_2O is important because changes in stratospheric H_2O have been shown to affect surface temperature, and it has been suggested that the decrease in stratospheric H_2O during the decade 2000–2009 slowed the rate of global surface temperature increase by ~25%.

With the recent upgrades to the instruments and continued support from the Navy and NASA, this network will extend the long-term data set and advance our understanding of the middle atmosphere.

[Sponsored by the NASA Upper Atmosphere Research Program and ONR]

Exploring the Impact of Explosions on Earth's Ionosphere

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Introduction: Earth's ionosphere, the ionized portion of the thermosphere (~80 to 1000 km altitude), is frequently perturbed by neutral buoyancy and acoustic waves originating in the lower atmosphere. These waves manifest as thermospheric neutral wind fluctuations that modulate the ambient ionospheric densities via ion-neutral collisions. The resulting ionospheric perturbations are commonly referred to as traveling ionospheric disturbances (TIDs). One source of these TIDs, which have been observed for decades using high frequency (HF) radiowave Doppler sounding techniques, is human-made explosions. For the purposes of comprehensive global explosion monitoring, HF Doppler sounders are somewhat limited in their detection range and portability. Consequently, other techniques have been explored to augment the detection capabilities of the explosion monitoring network.

In recent decades, remote sensing of line-of-sight total electron content (TEC) with GPS receivers has become a rich field of study. Networks of GPS receivers have been used to characterize TEC fluctuations resulting from TIDs generated by an array of geophysical phenomena including earthquakes, strong tornadoes, bolides, and orographic gravity waves. Recently, GPS data were used to detect the TID associated with an underground nuclear explosion (UNE). This has rejuvenated interest in ionospheric monitoring of explosions. However, there are a number of questions regarding why such a TID develops and what it might tell us about the explosion that generated it. With this in mind, a basic research program was initiated at the U.S. Naval Research Laboratory (NRL) to better understand the physics of the ionospheric ion-neutral coupling processes and how these processes impact GPS-based measurements of ionospheric fluctuations.

For example, the acoustic waves from smaller explosions do not penetrate as far into the upper atmosphere as those from larger explosions. Thus, smaller events impact mainly the bottom-side ionosphere (altitudes ~100 to 120 km), resulting in much smaller observable TEC perturbations.

GPS Signal Processing: A new GPS TEC data signal processing technique to identify potentially weak coherent signals, embedded within geophysical background noise, is shown in Fig. 6. The first step in this processing is plotted in the upper panel, which shows the GPS TEC time series from a single satellite/receiver pair near the 2009 North Korean UNE (detonation time 0.9 UT). To increase signal contrast and remove instrumental biases, the measurements were first processed with a parameterized finite differencing method. Two clear pulse-like disturbances are seen near 1.4 and 1.7 UT. In the second step, the spectral characteristics of these signals, with multiple peaks corresponding to acoustic wave periods of ~2 to 4 minutes, are shown in the lower panel. In this technique, the signals from many different satellite/receiver pairs in the vicinity of a suspected event can also be coherently combined to increase the signal-to-noise ratio and further improve the detection threshold of any corroborating signals (e.g., seismic, infrasound).

When the technique was applied to historical GPS TEC measurements in the vicinity of seven UNEs and seven large historical chemical explosions, acoustic-like TIDs were found for two of the UNEs and three of the chemical explosions, with as many possible/marginal detections. The level of background ionospheric activity was tentatively identified as the chief limiting factor to detectability.

Simulations: To better understand why TIDs were not observed in the GPS TEC measurements for all 14 events, the physics of the TID generation processes is being investigated by coupling a 3-D far-field acoustic blast wave propagation model with a high-resolution version of NRL's first-principles SAMI3 ionospheric model.[1] An example of the calculations for the ionospheric impact of the 2009 North Korean UNE (using published approximate source characteristics) is shown in Figs. 7 and 8. To compare with results published by Park et al.,[2] Fig. 7 shows the third-order time derivative of TEC (the metric used by Park et al.) at a location approximately similar to example GPS observations shown by Park et al. The initial disturbed state of this time series is a computational artifact as the simulation "settles down." Following the blast at 0.9 UT, a short disturbance is apparent with an arrival time and amplitude similar to what was observed by Park et al. Figure 8 displays a SAMI3-generated latitude/longitude snapshot of the TEC disturbance, something that could not be generated with the available GPS data due to the sparse coverage of receiver stations in the region. One can see clear north/south asymmetry due to the south-

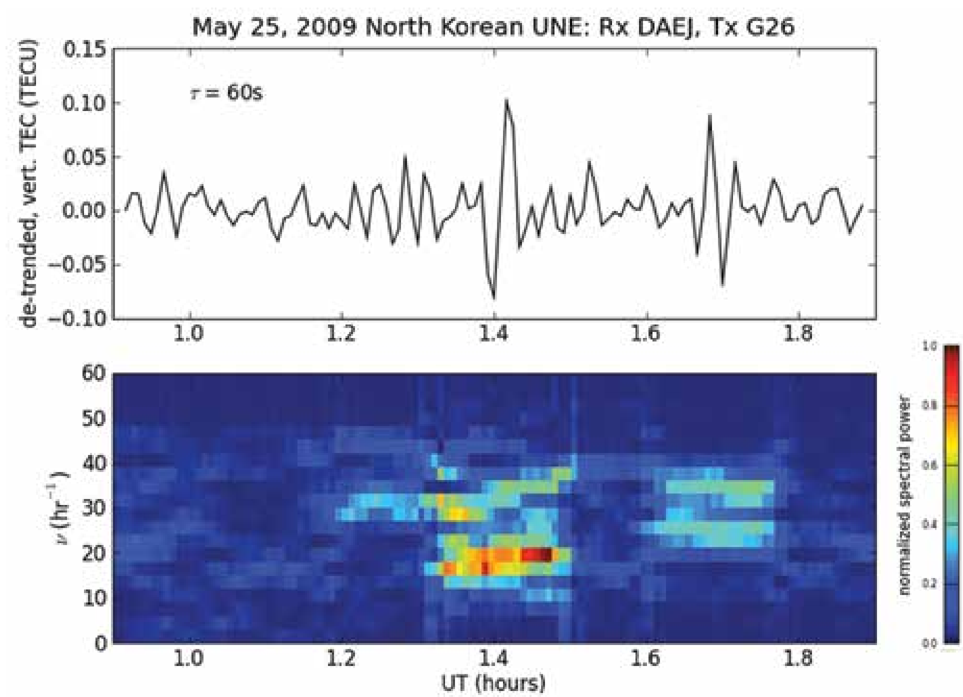

FIGURE 6
Example GPS time series analysis near the 2009 North Korean underground nuclear test. The upper panel shows the time series for the line of sight from a single receiver (station code DAEJ) and satellite (G26) roughly 800 km from the blast site. This shows TEC de-trended with a finite differencing method tuned to optimize fluctuations with periods of 2 minutes (2 × τ). The lower panel shows a fluctuation spectrogram of this time series, computed with a fast Fourier transform and a 10-minute sliding window.

ern portion of the wave having a velocity vector nearly parallel to the Earth's magnetic field.

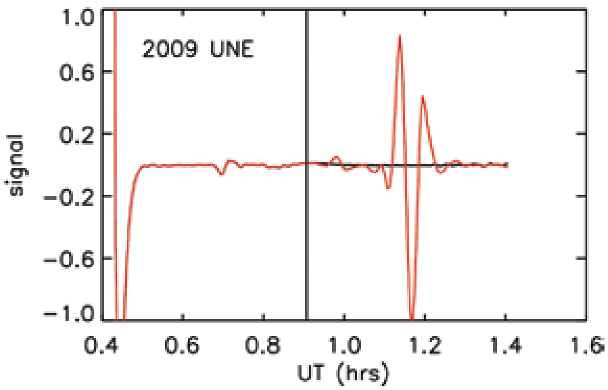

FIGURE 7
A time series from a TID simulated with the modified SAMI3 model, patterned after the 2009 North Korea UNE, a few hundred kilometers from the blast site. The quantity plotted is the third-order temporal derivative of TEC, the same metric used by Park et al..[2] The initial, large fluctuations are computational artifacts; the detonation time is marked with a vertical black line.

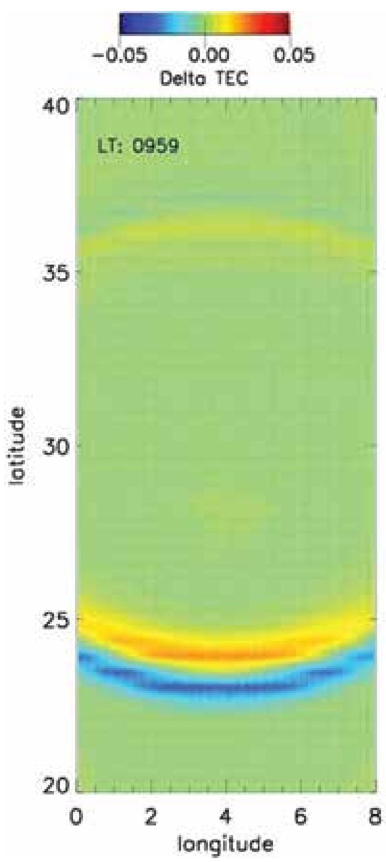

FIGURE 8
A map of the SAMI3-simulated TEC disturbance, patterned after the 2009 North Korean UNE, 30 minutes after detonation. The quantity shown, delta-TEC, is the difference in TEC between that simulation and one for the same time frame and location, but with no TID.

Summary: These recent research results provide new insights into the physics of the interaction between explosion-generated infrasound waves and the ionosphere, and how this knowledge can be incorporated into the next generation of a comprehensive global explosion monitoring system. The fact that a detection probability of ~30% to 50% was found using spectral analysis of publicly available GPS data for historical events demonstrates that the technique can provide useful corroborating information for explosion detection and event discrimination to supplement other primary explosion monitoring network means. Results from first-principles calculations with the SAMI3 model also indicate that there is at least a rudimentary understanding of the physical processes involved to be able to interpret the GPS TEC signals (or lack thereof) for similar events at others times and locations around the globe.

[Sponsored by the Defense Threat Reduction Agency]

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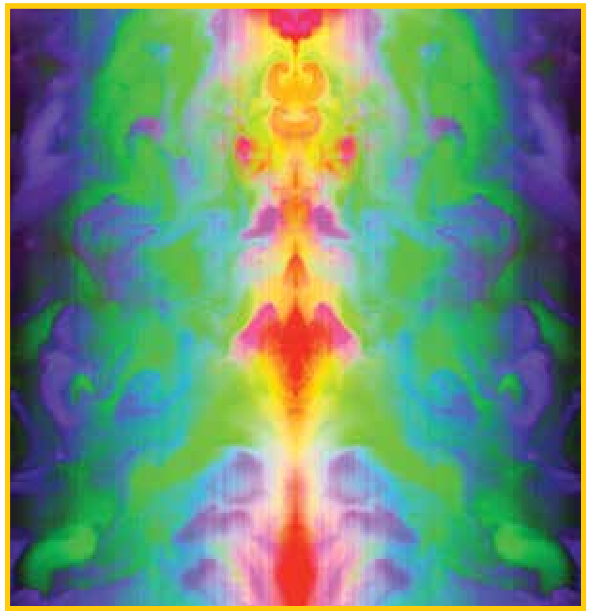
Simulation, Computing, and Modeling

NRL SCIENCE AS ART CONTEST

Remote Sensing Division Choice



Abstract Coastal Dynamics

This abstract image depicts sand, water, and foam mixing along an ocean coast. The image was constructed in a kind of cut-and-paste technique that began with imagery data taken along the coastline south of Christchurch, New Zealand, by the Hyperspectral Imager for the Coastal Ocean (HICO), the first space-borne imaging spectrometer designed to sample the coastal ocean. The coastline is in the center of the mirrored images, and the colors correspond to key components of dynamic coastal mixing: blue is clear water, green is water with entrained sand from the beach, and red is surf foam. Developed by the U.S. Naval Research Laboratory, HICO collected more than 10,000 images in its five years of operation, from its launch in 2009 until operations ended in 2014.

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Real-Time Targets in Hardware-In-The-Loop Antiship Cruise Missile Simulations

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Introduction: The U.S. Navy's requirement to evaluate the survivability of their combatant fleet necessitates missile engagement simulations of such fidelity that they can predict not only whether a ship will be hit, but where it will be hit. A new simulation capability is now available for a variety of naval vessel and threat missile combinations that features unprecedented target representation fidelity. This is especially important as threat missiles become increasingly sophisticated and are able to discern between different targets. Decades of research performed by the Tactical Electronic Warfare Division (TEWD), the Radar Division, and the Information Technology Division at the U.S. Naval Research Laboratory (NRL) have come together to permit the deployment of real-time, high-fidelity representations of radio frequency (RF) ship signatures for hardware-in-the-loop simulations within TEWD's Central Target Simulator (CTS) facility.

CTS is used primarily for assessing the effectiveness of countermeasures designed to defeat radar-guided antiship cruise missiles. Simulated radar returns of ship targets, passive decoys, and active jamming devices are broadcast at radio frequencies via 225 antennas mounted on one side of a large anechoic chamber (shown in yellow in Fig. 1). The antenna array provides the capability to radiate returns from multiple, spatially separated targets distributed over a large field of view. Located 75 feet away on the opposite side of the chamber is a three-axis flight motion simulator onto which the simulator receiver hardware is mounted (Fig. 2). Feedback from the missile simulator, including guidance commands and state changes, controls the flight motion simulator and impacts the characteristics of the simulated target returns. The output of each simulation run is a miss distance that quantitatively indicates the effectiveness of the countermeasure being evaluated.

FIGURE 2
Flight motion simulator within CTS.

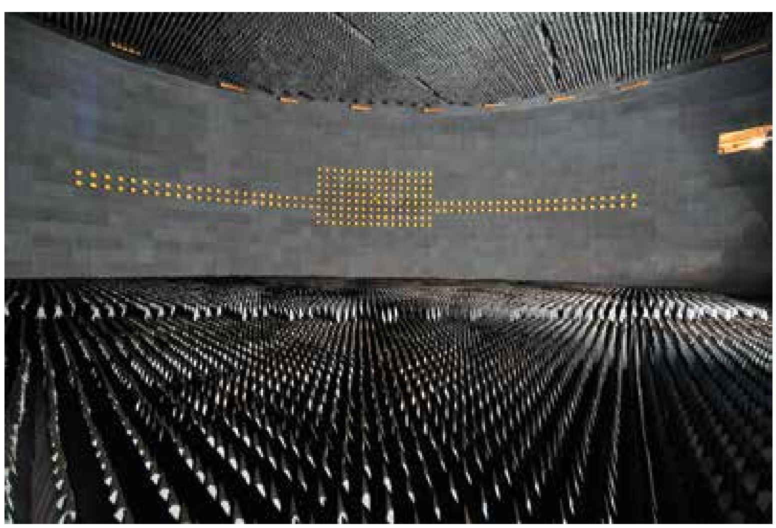

FIGURE 1
Interior of the Central Target Simulator (CTS).

Approach: Historically, only square-pulse representations of RF ship targets have been used in CTS due to speed limitations of computers and RF modulation hardware. As technological improvements have become available, various methods of creating shaped pulses have been undertaken. Five years ago, target signatures were precomputed based on the initial geometry and a fixed approach trajectory using the *CRUISE_Missiles* simulation. *CRUISE_Missiles* is a digital simulation of the entire threat engagement developed by TEWD's Advanced Techniques Branch.[1] It couples RF ship signature representations with high-fidelity, physics-based models of missiles and environmental effects in an event-driven simulation. *CRUISE_Missiles* relies internally on a customized version of the Radar Division's Radar Target Signature (RTS) model that has been optimized for runtime performance.

The RTS model is based on high-frequency scattering techniques developed specifically for ships in a sea multipath environment. The model is a set of analytical computer programs that convert a detailed geometrical description of a ship into its RF signature. This is done by decomposing its structure into basic geometrical shapes (e.g., polygons, cones, and cylinders) and coherently summing the contributions of these shapes while accounting for multiple-bounce interactions. This allows computation of the time-varying radar signature, given the precise relative position of the scatterers and the orientation of the ship.[2]

To generate real-world RF target signatures in the CTS chamber, extremely high fidelity representations of the aspect-dependent radar cross section (RCS) of the ship must be computed at the pulse repetition frequency of the radar receiver. Beginning in 2014, collaborative research between TEWD's Integrated Electronic Warfare Simulation Branch and the Advanced Techniques Branch accelerated the calculation of high-fidelity RF ship signatures in CTS. This effort has reduced the time to calculate the signature to the point where it can be generated for each pulse repetition interval. The ability to provide real-world target signatures in a true closed-loop environment has had a profound impact on the simulation fidelity in CTS by offering the flexibility for changing the RF signature in response to missile maneuvering and to dynamic changes in the missile behavior resulting from real-time responses of the missile to its perceived environment.

The Linux computers generating the RF signatures for CTS run a suite of multithreaded applications, collectively called *Real-Time_Targets*, using the RedHawk Linux real-time operating system. *Real-Time_Targets* receives up-to-date target-threat geometry from the main CTS simulation computer and returns a complex-valued, time-varying representation of the target signature over multiple range bins.

The RCS calculations include effects of both the ship-to-missile geometry and the environment. An advanced solid-body motion model predicts the sea-state-dependent position and orientation of the ship with respect to the missile. Environmental effects include the impact of ocean surface roughness on the return and the constructive and destructive interference between the direct and indirect radar returns. This allows an accurate prediction of the scene geometry and a reliable estimate of the target signature.

The normalized time-domain representation of the radar cross section is fed to a high-speed digital-to-analog converter which drives an RF vector modulator to shape each portion of the target pulse (Fig. 3). The maximum RCS is delivered to the main CTS simulation computer, which is responsible for computing the radar range equation. It takes into consideration all the remaining elements of the RF interaction in order to determine which antennas to employ and at what power levels. The main CTS simulation computer controls the amplification of the RF signal which is then sent to the antennas.

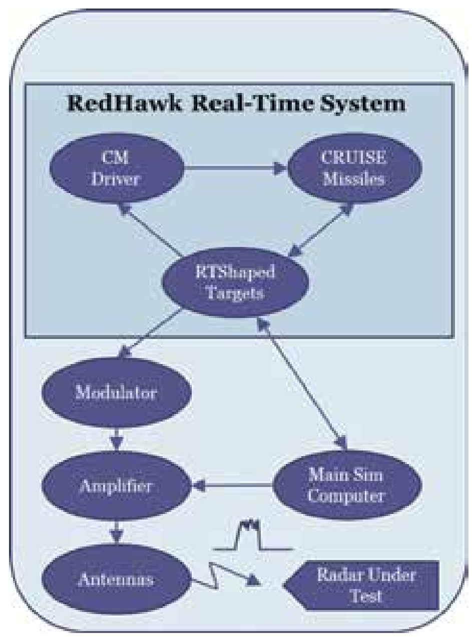

FIGURE 3
Real-Time_Targets software architecture diagram.

As implemented in CTS, *CRUISE_Missiles* uses a multithreading implementation called Open Multi-Processing to distribute the independent computation of the contributions of the many hundreds of individual sub-shapes of the ship across 12 computer cores.[3] A separate process, *CM Driver*, receives scenario state information from the broader simulation via *RTShaped Targets* and creates the scenario input file for the *CRUISE_Missiles* process for each individual scenario run.

Conclusions: Powerful Linux workstations utilizing real-time operating systems, combined with high-speed waveform generators, now permit the computation and generation of target signatures in TEWD's Central Target Simulator with unprecedented fidelity. This dramatically improves NRL's ability to synthesize realistic targets in CTS, enhances the validity of test results, and gives the U.S. Navy better insight into interactions between missiles, ships, decoys, and countermeasures.

[Sponsored by ONR under the ENEWS Program]

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Radiation Signatures of Intermittent Subresolution Coronal Activity

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Introduction: Solar theorists have increasingly converged on the idea that bursty events at very small spatial scales underlie energy dissipation in the corona (the outer atmosphere of the Sun). However, the theory, which is based on magnetohydrodynamics (the study of electrically conducting fluids) has not, until now, been able to make the crucial link with what is observed, namely, radiation. Researchers at the U.S. Naval Research Laboratory (NRL), working with an international team, have been able to make that link. Numerical simulations using the new HYPERION code have shown that a large number of coherently triggered, coronal heating bursts can be produced by motions at the solar surface (the photosphere). Synthetic observations that produce the radiation due to these events have been calculated from the computational results and analyzed using techniques developed for the analysis of solar and stellar observations. The results provide the first true theoretical predictions, that is, emission measures, for solar coronal heating theory.

Coronal Heating: Based on laboratory experiments, researchers can link radiation emission lines to particular temperatures. Beginning about 100 years ago, observers noted many of these same emission lines in various regions of the solar atmosphere. As a consequence of these observations they inferred that the solar corona (<1,000,000 degrees Kelvin) is much hotter than the underlying photosphere (~10,000 degrees Kelvin), the part of the Sun visible to the naked eye. This conclusion seemed counterintuitive: shouldn't the temperature decrease radially as distance increases from the nuclear furnace at the Sun's core?

Hence, some explanation for this phenomenon was needed. Radiation cannot explain radiation, the radiation is a consequence of some other process. The most straightforward thermodynamical process, thermal conduction, likewise cannot explain this phenomenon, since heat would be conducted from the hot corona to the relatively cool photosphere.

Most explanations for the high temperature of the corona have settled on invoking the Sun's magnetic field. These theories rely on modeling the solar atmosphere as an electrically conducting fluid. The study of such fluids is called magnetohydrodynamics (MHD). Many theories based on MHD rely on turbulence to explain the heating. Fluid motions in the Sun's photosphere move the magnetic fieldlines, creating a surplus of magnetic energy in the corona. This energy is transformed into thermal energy by a process called magnetic reconnection, which occurs intermittently in a magnetofluid characteristic of the solar corona.

Recent Results: Until now there has been something of a language gap between observers, who think in terms of radiation, and theorists, who use terminology relating to waves and turbulence. We have been able to bridge this gap by using the HYPERION code and applying observational plasma diagnostics, such as computing differential emission measure distributions with Monte Carlo Markov Chain techniques.[1] HYPERION solves the MHD equations with a new parallelized, viscoresistive, three-dimensional compressible MHD code. The code employs a Fourier collocation — finite difference spatial discretization — and uses a five-step fourth-order Runge-Kutta temporal discretization.

In this context, the most important information that numerical simulations with HYPERION provide is numerical predictions for coronal temperature and electron number density (see Fig. 4) that can be used, in combination with a database of atomic transitions, to obtain synthetic observations of the corona (Fig. 5).

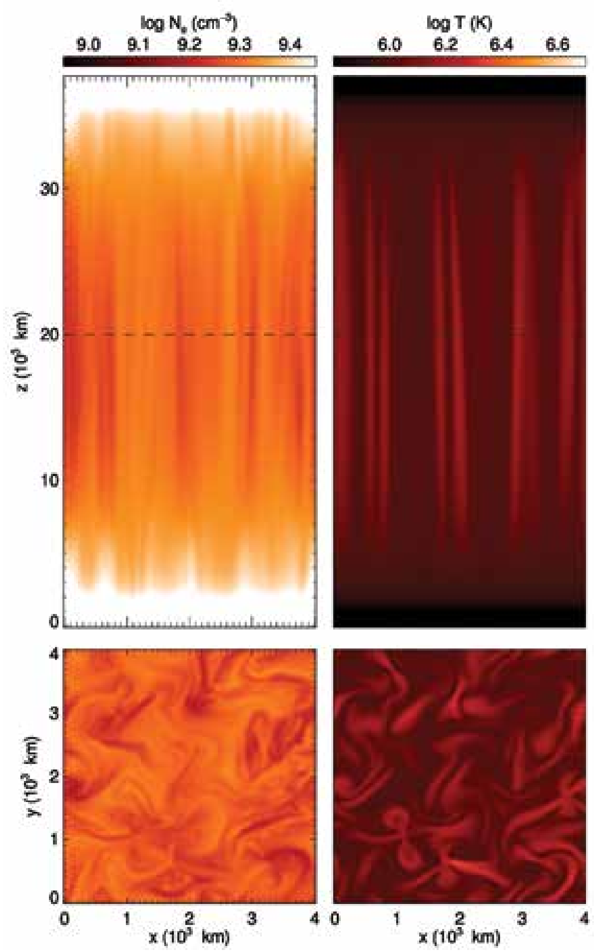

FIGURE 4

Typical electron number density (N_e) and temperature (T) data from the HYPERION code. The top panels show data along a plane parallel to the axial magnetic field of the atmosphere's building blocks: coronal loops. The bottom panels show data perpendicular to the loop's axial magnetic field at the loop apex.

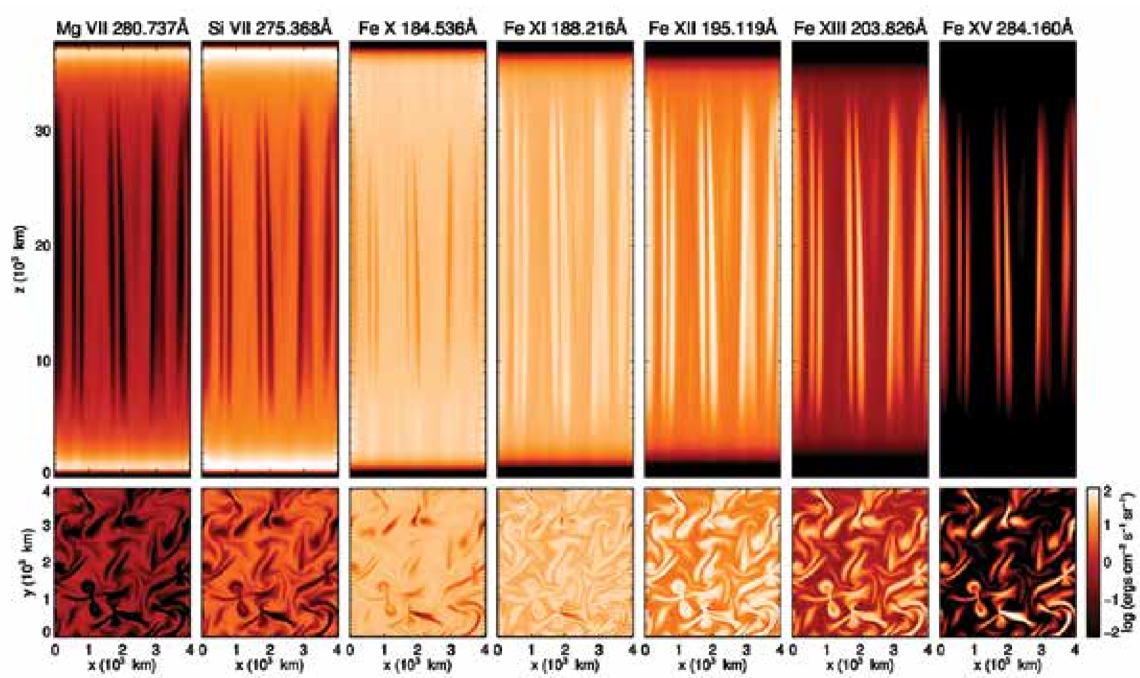

FIGURE 5

Sample of synthetic observations. These panels show how the coronal loops would appear in various extreme-ultraviolet emission lines observed by a space instrument. The orientations here are the same as in Fig. 4.

Interpretation of direct comparisons between observed and synthetic intensities is complex. A better insight about the elusive heating process is obtained when comparing their emission measure, a diagnostic of the plasma distribution in temperature space along the line-of-sight of our telescope (Fig. 6).

We computed emission measures using the Monte Carlo Markov Chain algorithm and found that the HYPERION simulations of surface fluid motions followed by energy transfer and dissipation through reconnection are able to reproduce fundamental characteristics of the plasma distribution in the corona as observed with current instrumentation (see Fig. 6).

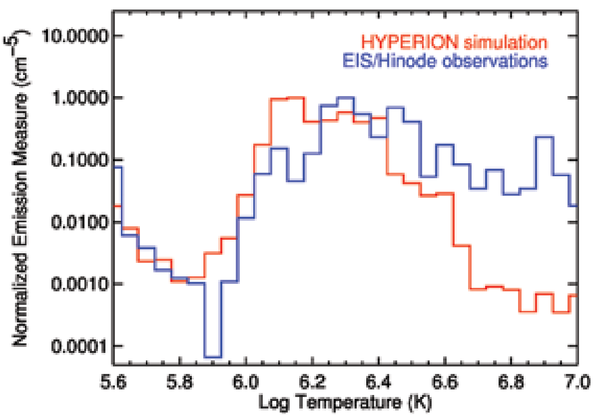

FIGURE 6
Comparison of the emission measure calculated from HYPERION simulation results and the one obtained from the Extreme Ultraviolet Imaging Spectrometer (EIS) aboard Hinode in a solar active region.

Future Work: Our work represents a beginning attempt at understanding one of the most important and challenging problems in solar physics. Much further research needs to be done. For one thing, we need to explore how the radiation varies with loop length and magnetic field strength. For another, we need to experiment with other forms of motion at the base of the structures. The present form of the motion does not allow for the storage of magnetic energy in the interior of the loop system, and hence events with larger energy releases, such as flares, do not occur.

[Sponsored by the NRL Base Program (CNR funded) and NASA]

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Gravity-Assisted Heat Pipes for Thermal Protection of Hypersonic Leading Edges

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Spacecraft Engineering Department

Hypersonic Heating: At the U.S. Naval Research Laboratory (NRL), the Naval Center for Space Technology's Thermal Systems Analysis Section (TSAS) within the Spacecraft Engineering Department is actively developing integrated thermal management technology for hypersonic cruise and atmospheric entry vehicles. The primary concern in the hypersonic flight regime is the intense heating and temperatures encountered, which precludes the use of conventional aerospace materials. TSAS's approach, building on early work performed at Los Alamos National Laboratory and NASA in the 1980s and 1990s, is to passively remove the concentrated heat from the leading edge and thereby reduce the peak temperature that a vehicle must be designed to endure. Key resources that support this work include a High Performance Computing system with commercial and NRL-developed software to perform computational fluid dynamics, finite difference heat transfer, finite element structural stress, geometric modeling, and flight conditions analysis for hypersonic cruise and atmospheric entry. A sample continuum flow model for a Mach 6 hypersonic waverider is depicted in Fig. 7, illustrating its shock wave and temperature field. TSAS maintains the state-of-the-art Two-Phase Heat Transfer Laboratory for integration, testing, and model correlation to complement the theoretical and computational analysis of thermo-fluid systems.

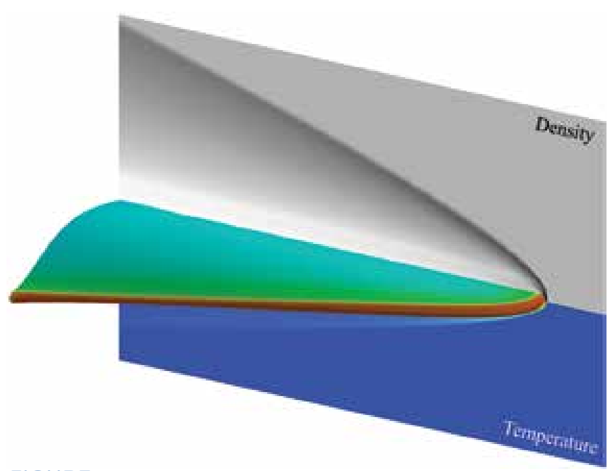

FIGURE 7
Air density and air and vehicle surface temperature contours for a high-lift Mach 6 hypersonic waverider at 30 km altitude with heat shield aeroshell.

Hypersonic Aerodynamics: The speed of sound is the speed at which disturbances propagate through a fluid, approximately 343 m/s (767 mph) for air near sea level. Supersonic objects travel at faster speeds, characterized by the creation of a shock wave around and trailing the supersonic object due to compression of the flow. Air pressure jumps significantly across a shock wave, resulting in dramatically different aerodynamics than for subsonic vehicles. Flight speed is described as multiples of the speed of sound, known as Mach number. Lift and drag forces increase cubically with speed, so higher velocity vehicles tend to be very streamlined in order to minimize the effect of drag. The hypersonic regime is encountered at speeds high enough that the compression and viscous heating of air becomes a significant factor, loosely defined as Mach 5 and above. Vehicles with sharper geometry encounter extreme heating at lower speeds, whereas blunt geometry may delay high temperature effects until a higher Mach number, at the expense of higher drag.

Materials and Heat Transfer: The three methods of heat transfer are conduction, convection, and radiation. Conduction is the movement of thermal energy through static material due to a gradient in temperature; convection is the transport of thermal energy due to the movement of fluid; and all objects exchange radiative heat based on their geometry, surface properties, and temperature differences between surfaces. Surface chemistry, oxidation, and melting of vehicle surfaces become primary concerns in the hypersonic regime, where temperatures are often well above 1000 °C. Peak temperatures are heavily dependent on Mach number, and can quickly exceed the service limit of the highest melt-temperature materials. Air begins to dissociate at just 1700 °C, depending on ambient pressure, and dissociated oxygen is highly reactive with vehicle surfaces.

Heat Pipes and Two-Phase Heat Transfer: A heat pipe is a heat transfer device in which a solid, sealed case material contains a working fluid under its own pressure in both liquid and vapor phases. Heat is conducted through the case wall to evaporate the liquid, and the vapor travels through a hollow core to a heat sink where it condenses back into liquid. The thermal energy is conducted through the wall into the heat sink, and the newly condensed liquid is driven back to the evaporator by either gravity or capillary forces. Gravity, acceleration, and capillary forces can each act to aid or impede the flow of liquid back to the evaporator. Heat pipes can be made in various geometries and configurations of walls and wicking structures and have no mechanical moving parts to wear out or break down. A schematic for a leading edge configuration is presented in Fig. 8. The heat transport capability for large aspect ratios can yield an effective thermal conductivity many orders of magnitude higher than that of the best solid materials. Working fluids are chosen based on advantageous physical properties and their temperature range. Candidate working fluids for the hypersonic regime include the alkali metals sodium, lithium, potassium, and cesium.

Heat Pipe Thermal Protection of the Hypersonic Leading Edge: Conventional reusable heat shields for hypervelocity and atmospheric entry vehicles consist of thick, temperature-resistant, low-conductivity materials that form a thermal barrier between the high-temperature aeroshell and the internal airframe that cannot survive such extreme conditions. The blockage of thermal energy flow drives up surface temperatures dramatically, particularly at the leading edge where the aerothermal heat flux is concentrated. These extreme conditions require materials with sufficient service temperatures and very blunt geometry, which increases aerodynamic drag. Alternatively, the peak temperature may be reduced by increasing the effective thermal conductivity of the aeroshell with embedded or integrated heat pipes. The leading edge heat pipe conforms to the internal geometry of an airfoil, conducting heat from the highly concentrated leading edge and moving

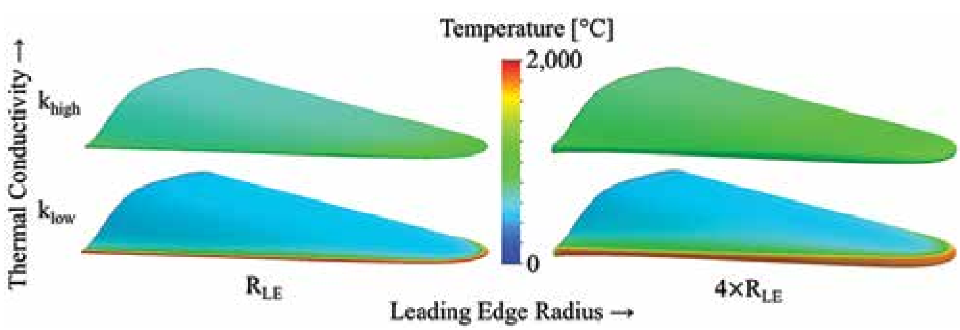

FIGURE 8
Liquid evaporates at the high heat flux leading edge and moves the thermal energy downstream to keep leading edge temperatures low. Vapor condenses along the cooler wall and liquid is returned to the leading edge via a capillary wick inner lining or a deceleration force.

it to the cooler wall downstream. Disallowing thermal energy buildup results in a significantly lower maximum temperature. Preliminary aerothermal models demonstrate the capability of effective thermal conductivity enhancements to outperform the temperature reduction resulting from blunt geometry — without increasing drag. An example is presented in Fig. 9, where maximum temperature is compared for variations in leading edge radius and effective thermal conductivity. Temperature reductions enable the use of less expensive, more conventional materials and the attainment of faster hypersonic speeds. Ongoing efforts are applying these concepts to vehicles in dense and rarefied atmospheres across hypersonic flight through atmospheric entry, Mach 5 to 25.

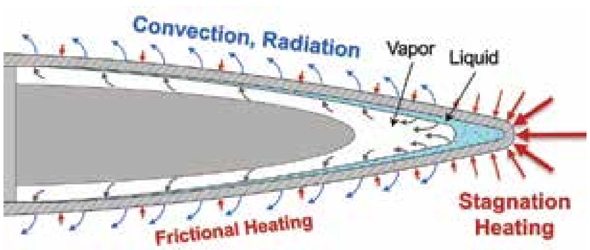

FIGURE 9
Surface temperature contours for a high-lift Mach 6 hypersonic waverider with varied leading edge radius and effective thermal conductivity: 1 W/m/K typical of high-temperature composites compared to 100 W/m/K effective aeroshell with embedded heat pipes.

[Sponsored by the NRL Base Program (CNR funded)]

Thermal and Fluid Flow Instabilities of Loop Heat Pipes and their Effects on Operation

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Introduction: Loop heat pipe (LHP) technology has become the mainstay of spacecraft thermal control systems. An LHP is a self-contained capillary heat transport device having no mechanical parts to wear out, break down, or require lubrication to operate. Hence, LHPs are highly advantageous for unmanned space missions that compel all subsystems to meet reliability and lifetime requirements. In addition, LHPs offer orders-of-magnitude improvement over conventional heat pipes in performance, integration and testing, and operational versatility.

Satellites implement higher density electronics than ever before, putting greater demands on thermal control systems. This requires loop heat pipes to be run at lower temperatures. LHPs work well at room temperature, but at temperatures below −15 °C, significant oscillations can occur. Two types of temperature oscillations have been observed in LHPs: high-frequency/low-amplitude (HFLA) and low-frequency/high-amplitude (LFHA). Low-frequency/high-amplitude oscillations are often attributed to a large thermal mass attached to the evaporator and a low applied heat load, as revealed by ground test data from the NASA Jet Propulsion Laboratory (JPL) propylene LHP.[1] Causes of high-frequency/low-amplitude oscillations have not yet been positively established. New theoretical and experimental work at the U.S. Naval Research Laboratory (NRL) is leading to a better understanding of these LHP instabilities.

Numerical Model of Loop Heat Pipes: The basic operation of an LHP is illustrated in Fig. 10. Heat from a heat source (e.g., an electronics box) conducts through the capillary pump metal casing to vaporize liquid in the primary wick. The vapor generated on the outer wick surface travels along the vapor line to the condenser, where heat is removed and the vapor condenses back to the liquid phase. The liquid exits the condenser and flows in the liquid line back to the capillary pump to complete the cycle.

LHPs are generally analyzed as steady-state systems. At first glance, the LHP seems like a simple heat transport device. However, the interaction among the phase change mechanisms, heat transfer, and fluid dynamics in the loop forms a complex dynamical system. To capture the dynamics of LHPs, NRL formulated a new theory and new numerical model. The new model treats the LHP as one single dynamical system that has a multitude of mechanisms capable of modulating the loop dynamics individually. A transient model was developed culminating in a set of seven coupled ordinary differential equations to describe the fluid and thermodynamics and heat transfer throughout the loop, and one coupled partial differential equation to describe the condensation, liquid sub-cooling, and liquid line warming.[2,3]

NRL compared the model to published data from the JPL Tropospheric Emission Spectrometer (TES) LHP and the Goddard Space Flight Center Mini LHP. The model's predicted range of instability matches with 22 out of 23 JPL TES LHP test cases, as shown in Fig. 11 (right). The one case that does not match is on the boundary of the predicted oscillatory region where a small change in LHP parameters can change the LHP operation from steady state to oscillatory. The model is also able to closely predict the frequency of the oscillations of the JPL TES LHP, as shown in Fig. 11 (left).

In addition to a detailed derivation of the governing equations, NRL's theory established two LHP

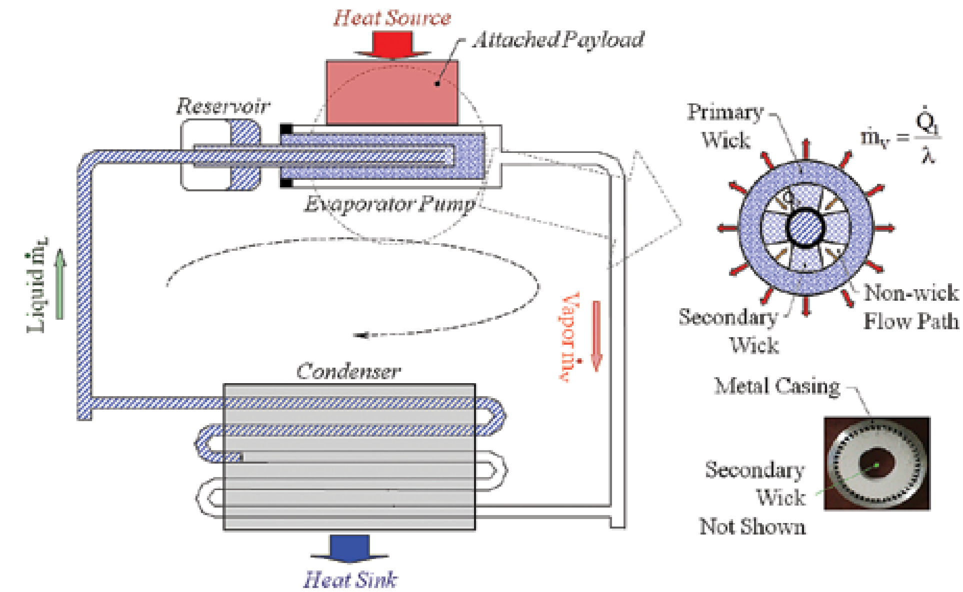

FIGURE 10
Schematic of loop heat pipe operation.

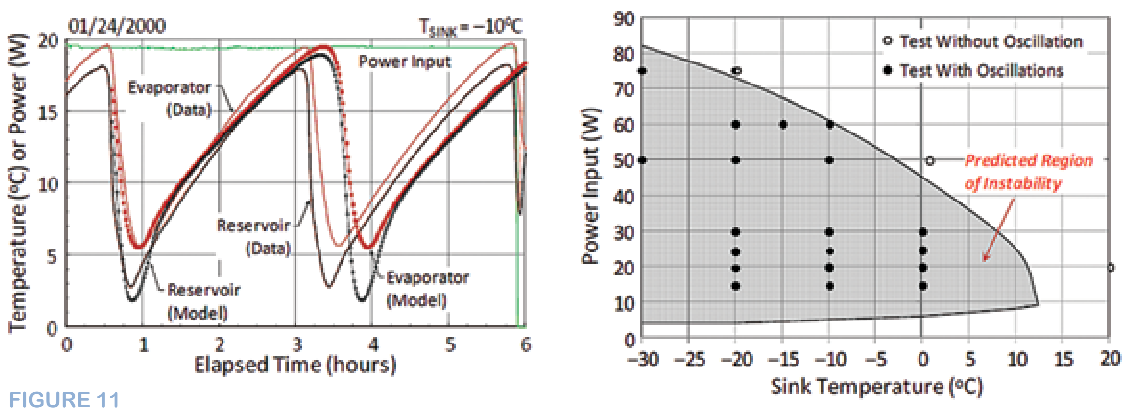

FIGURE 11
NRL model predictions compared to JPL TES LHP test data. Left: Model predictions compared to test data of oscillation frequency and amplitude at 20 W with a sink temperature of −10 °C. Right: Model prediction of instability region compared with test data.

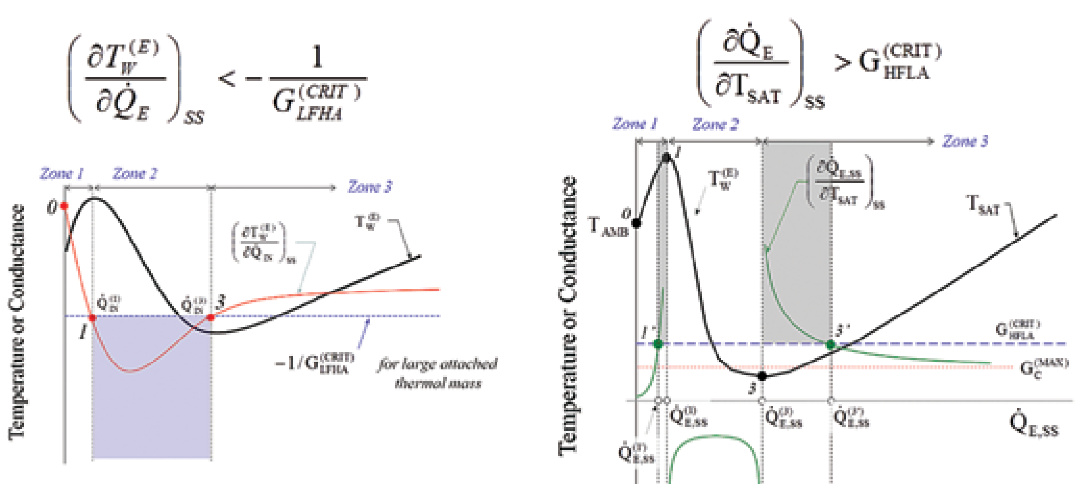

FIGURE 12
Loop heat pipe stability criteria for low-frequency/high-amplitude (left) and high-frequency/low-amplitude (right) oscillations. The blue and gray regions are predicted regions of instability in LHP operation as a function of input heat flux. References 2 and 3 provide details of the stability analysis.

instability criteria for the LHPs, one for each oscillation type, capable of predicting the operating conditions under which the temperature oscillations will occur, as shown in Fig. 12.[2,3] The figure shows the operation of an LHP as heat flux is increased and the three regions of instability (blue on the left and two gray areas on the right) that cannot be avoided. The figure shows stable operation is possible at high heat flux.

Experimental Validation: An experiment is under way at NRL to validate the new model. An LHP is set up with a resistive heater applied at the evaporator and a chiller-controlled cold plate at the condenser. The entire assembly is thermally isolated with insulation throughout testing to minimize environmental effects. Type K thermocouples are placed at various locations around the outside of the LHP. The chiller is set to control the cold plate at −20 °C, −10 °C, 0 °C and +10 °C, to test how the condenser temperature affects the development of oscillations in an LHP. The resistive heater on the evaporator is set to different power levels from 0 W to 500 W, depending on the condenser temperature, to test at what power levels the oscillatory behavior begins and stops.

Further testing will study the effects of varying the condenser temperature as though the LHP were operating in low Earth orbit (LEO). The heater on the evaporator will be varied to imitate the typical electronics duty cycles of a satellite in LEO. This experiment will evaluate how an LHP in LEO might display oscillatory behavior, and if it can operate without failure. The data from this test will also be used to validate the numerical model.

[Sponsored by the NRL Base Program (CNR funded)]

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Space Research and Satellite Technology

NRL SCIENCE AS ART CONTEST

Oceanography Division Choice

The State of the Ocean

Researchers in the NRL Oceanography Division dreamed up this image to capture the visual thrill that scientists get from looking at a scientific equation. For the nonscientist, an extravagant graffiti-like representation of something like $\rho=\rho_0[\alpha\Delta T+\beta\Delta S]$ — the seawater equation depicted here — might convey some of the splendor of meaning that resides for the scientist in a neat linear array of symbols and signs. In this case, ρ is seawater density, where ρ_0 is the reference density, α is the thermal expansion coefficient, β is the saline contraction coefficient, ΔT is the change in temperature from the reference state, and ΔS is the change in salinity from the reference state.

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Exploring and Exploiting the Space Environment with Novel Sensors and Coupled Modeling

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Relying On the Space Environment: Many military and civilian systems rely on the uppermost atmosphere or geospace that immediately surrounds the Earth. Skywave communication systems or over-the-horizon radar, for example, rely on the partially ionized regions of the upper atmosphere to reflect radio frequency signals back to Earth in order to achieve ranges of a few thousand kilometers or more. This so-called ionosphere is also a source of errors and outages for communication and for geolocation systems, such as the Global Positioning System (GPS). These applications generally rely on a quiescent upper atmosphere, that is, one with little spatial structure, turbulence, or temporal gradients, to minimize detrimental effects of scattering or multipath propagation.

Research over the last two decades has shown that the upper atmosphere responds not only to solar particle and radiation inputs but also to lower atmospheric meteorology. In particular, during periods of low solar activity, much of the ionosphere's rich spatial and temporal structure is driven by a spectrum of atmospheric wave disturbances emanating from the lower atmosphere. Predicting ionospheric weather therefore requires a whole atmosphere model that extends seamlessly from the ground all the way up to altitudes of 500 km and above. The Geospace Science and Technology Branch in the Space Science Division at the U.S. Naval Research Laboratory (NRL) is working on both next-generation whole atmosphere modeling and innovative space-based environmental sensors. The sensors will provide the models with necessary global datasets, just as data from weather satellites and thousands of weather stations all over the world both initialize and validate our daily tropospheric weather forecasts.

Modeling the Atmosphere Through Thick and Thin: Historically, our environment has been described using stand-alone models for different regimes. For example, there are individual models for the ocean, sea ice, land, the lower atmosphere where the air is thick and mainly controlled by fluid dynamics, and the upper atmosphere, where the air is much thinner, becomes partially ionized by solar radiation, and is therefore also subject to electromagnetic effects. Significant improvements in our forecasting capabilities can be achieved by coupling these models, or creating integrated models that seamlessly connect traditionally separate modeling domains.

NRL has created the HI-TIDES model (Highly Integrated Thermosphere Ionosphere DEmonstration System) to explore the lower atmospheric drivers of the ionosphere. HI-TIDES couples the operational Navy weather model (NAVGEM) and the extended Whole Atmosphere Community Climate Model (WACCM-X) to propagate atmospheric disturbances produced by underlying weather systems into the upper atmosphere (altitudes ~80–500 km), which in turn drive evolution of the electrically charged plasma components through direct coupling to the NRL ionosphere model, SAMI3.[1] First results were recently published by McDonald et al.[2] and confirm the potential of this coupling approach to reproduce major features of the ionosphere that are controlled by lower atmospheric drivers (see Fig. 1).

Models Need Data: The best forecasting results are typically achieved using physics-based models (such as HI-TIDES) and a large set of near-real-time sensor data that provide reliable initial conditions from which to propagate important environmental variables, as well as reference fields for verification and validation.

In the last decade, members of the NRL Geospace Science and Technology Branch have invented, developed, integrated, and tested over a dozen space-based environmental sensors that have been launched into orbit or are currently under preparation for launch. The majority measure upper atmospheric properties that are particularly valuable for initialization or verification of models. Figure 2 shows a timeline of relevant space-based sensors.

In particular, upper atmospheric temperature and the composition and chemistry of the upper atmosphere and ionosphere are measured by the Remote Atmospheric and Ionospheric Detection System (RAIDS) on the International Space Station (ISS), the operational Special Sensor Ultraviolet Limb Imagers (SSULI) that are deployed on DMSP (Defense Meteorological Satellite Program) satellites, and the upcoming Limb-Imaging Ionospheric and Thermospheric Extreme Ultraviolet Spectrograph (LITES) and GPS Radio Occultation and UV Photometry – Co-located (Group C) sensors, also on the ISS. Multiple miniaturized Small Wind and Temperature Sensors (SWATS) are performing in situ measurements of constituents and wind in the upper atmosphere. The Michelson Interferometer for Global High-resolution Thermospheric Imaging (MIGHTI) will conduct remote sensing measurements of neutral wind and temperature in the upper atmosphere from the NASA Ionospheric Connection (ICON) Explorer.

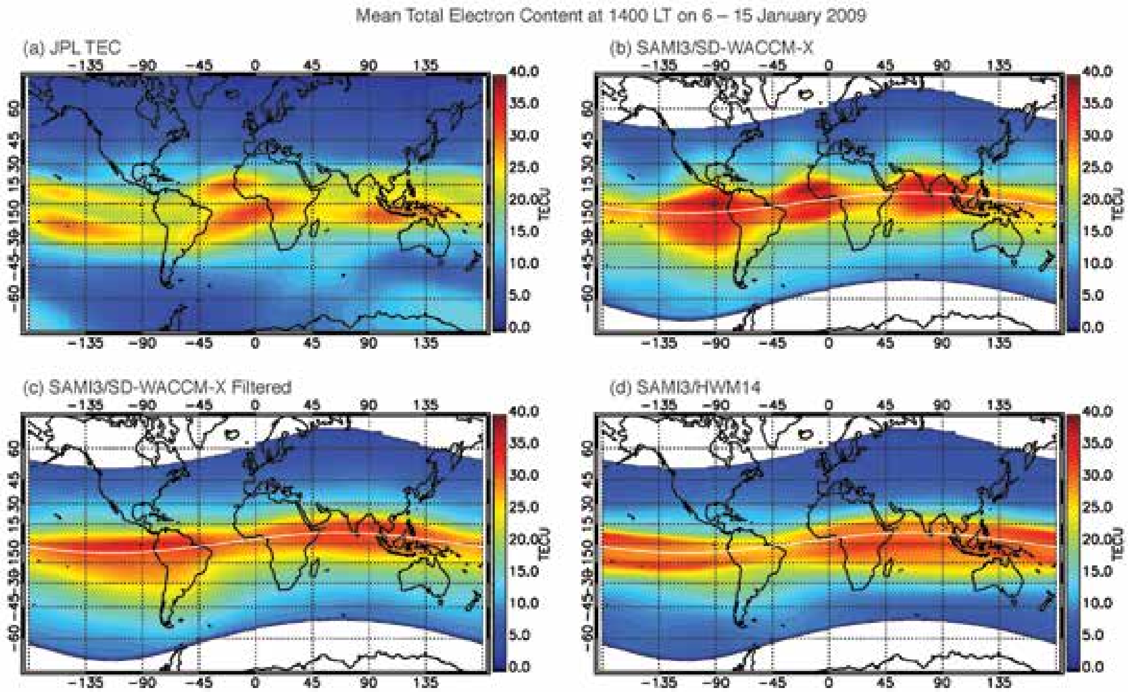

FIGURE 1

(a) Measured total electron column density (1 TECU = 10^{16} m^{-2}); (b) HI-TIDES model result showing similar three-peak structure as forced by lower atmospheric meteorology; no three-peak structure is seen when using incomplete forcing from below (c) or climatological winds (d) (HWM = Horizontal Wind Model).[2]

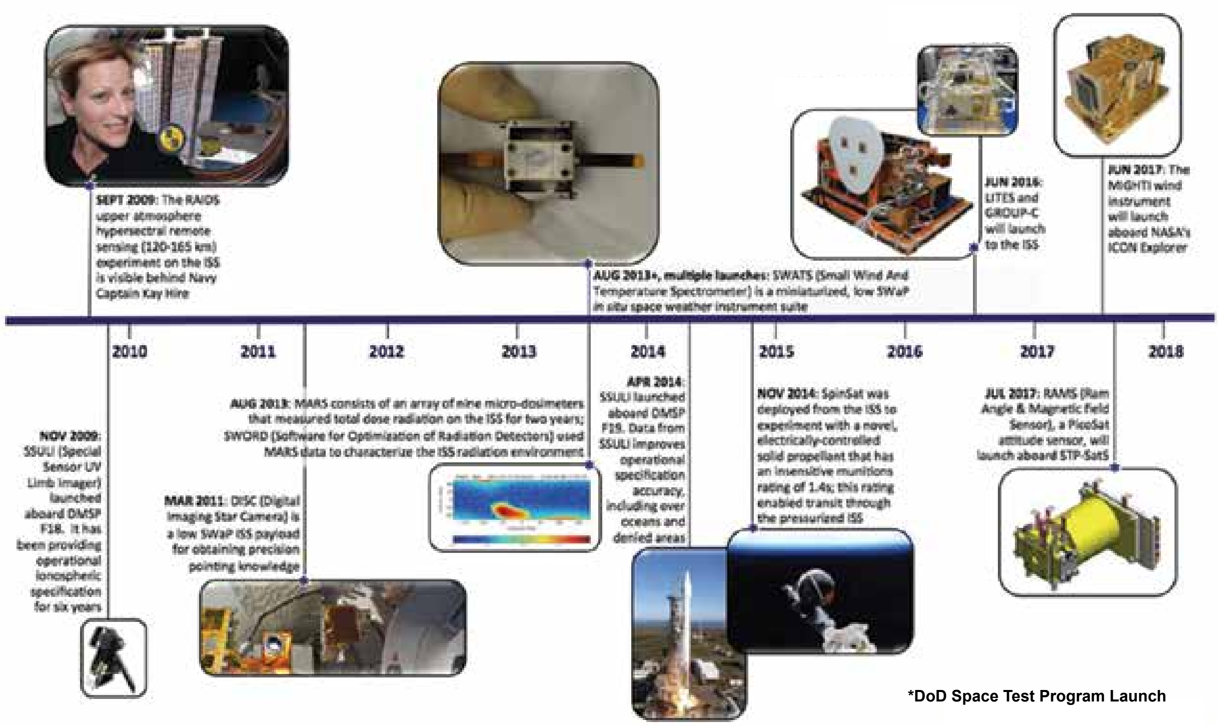

FIGURE 2

NRL Geospace Science and Technology (S&T) Branch space instruments and launch timeline.

Combined with the NRL high frequency (HF) raytracing model (MOJO-15), progress in ionospheric specification and forecasting will lead to unprecedented situational awareness capabilities to inform operations and decision making for our globally deployed Navy.

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Novel Scintillators for Astrophysical and Terrestrial Applications

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Introduction: The universe — from here on Earth to the farthest depths of space — is awash in a sea of radiation that spans the electromagnetic spectrum. Radiation can be categorized into two groups depending on how it interacts with matter: non-ionizing, such as radio, infrared, and optical; and ionizing, such as X rays and gamma rays. Short-wavelength, ionizing radiation, which strips electrons from atoms, is more energetic and hence more penetrating, and thus more difficult to detect, than non-ionizing types. Another form of ionizing radiation is the neutron that can become free via decay, fission, or spallation. Researchers in the High Energy Space Environment Branch of the U.S. Naval Research Laboratory (NRL) Space Science Division concentrate on the detection and measurement of ionizing radiation, specifically gamma rays and neutrons. Detecting ionizing radiation is more difficult than detecting non-ionizing radiation because for the former, we cannot use focusing optics. Using a standard telescope design results in the radiation passing through it like bullets. The most effective way to detect and measure ionizing radiation is to provide a medium through which the radiation can pass and produce ionization along its path. More specifically, the material should scintillate, or "light up," in response to ionizing radiation passing through it. The amount of light produced by the ionizing radiation yields information on the incoming energy of the stimuli. For certain materials, the type of ionizing radiation — either neutron or gamma ray — can be determined based on the time characteristics of the light pulse.

Instrumentation: Our work actively focuses on the development and testing of state-of-the-art radiation detection scintillation materials and scintillation light readout devices. Two scintillators we have investigated are strontium iodide doped with europium (SrI:Eu) and Cs_2LiYCl_6 doped with cerium (CLYC:Ce). SrI:Eu is an inorganic scintillation detector with the best energy resolution achievable with a commercial scintillation material (a full width at half maximum, FWHM, of 2.9% at 662 keV). Typical scintillation detectors used for gamma-ray spectroscopy have FWHM of ~7% at 662 keV or provide comparable energy resolution but are internally radioactive. CLYC:Ce is another inorganic scintillation material with very good gamma-ray energy resolution (FWHM of 4.5% at 662 keV) and the ability to discriminate between gamma rays and fast/thermal neutrons. CLYC:Ce represents an ideal scintillator if one's interest is in both neutrons and gamma rays because high-quality measurements can be made with a single instrument, as opposed to requiring two separate, often disparate instruments, to make high-quality measurements of both simultaneously.

A scintillation material that produces light in response to ionizing radiation is only part of the story, as one must then couple a light readout device to the material, and turn the light signal into a useful quantity (i.e., an electrical signal). Standard light readout is typically done with photomultiplier tubes (PMTs); these devices are often large and bulky, require high voltage, and are susceptible to magnetic fields. Newer light readout devices known as silicon photomultipliers (SiPMs) produce results comparable to PMTs in terms of signal gain, but are smaller in size, use low voltage, and are not susceptible to transient electromagnetic fields.

Applications: The purpose of developing this instrumentation is to make high-quality radiation measurements in astrophysical and terrestrial environments. Instruments sensitive to gamma rays or neutrons for astrophysical measurements need to make observations aboard satellites above the Earth's protective atmosphere. SrI:Eu serves as an excellent detection technology for the measurement of gamma-ray lines, needed for understanding cosmic nucleosynthesis, the extreme environments around black holes, or locally produced electron/positron annihilation photons from terrestrial gamma-ray flashes. The CLYC:Ce detector is ideal for simultaneously measuring fast neutrons and gamma rays from the Sun, facilitating our understanding of particle acceleration during solar flares (Fig. 3).

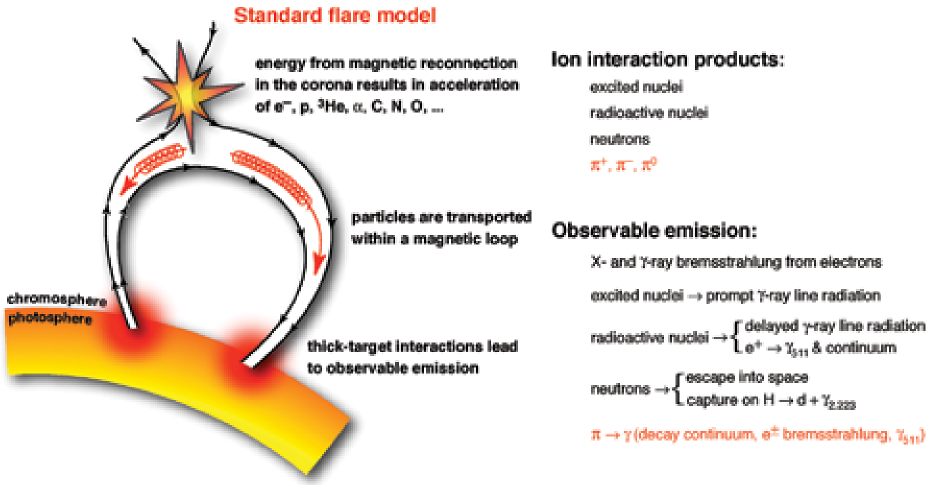

FIGURE 3
Illustration of the particle acceleration process occurring during a solar flare. Electrons, protons, and ions are accelerated down into the Sun's chromosphere, resulting in the production of neutral radiation.

On the ground, the instrumentation sensitive to the energy regime we have outlined is applicable for the detection of nuclear material. Gamma-ray and neutron emission detected above normal background levels in terrestrial environments could be an indication that illicit nuclear material is present. Understanding the spectrum produced by the material in question could be crucial for detecting and interdicting the contraband.

Future Work: In 2015 we completed the necessary laboratory work in advance of space qualifying a small SrI:Eu scintillator coupled to an SiPM. This instrument is set to launch on an upcoming Department of Defense Space Test Program satellite.[1] Extensive work was performed to fully characterize the instrument such that we can understand the effects the space environment will have on the instrument once in orbit. Figure 4 shows the bare SrI:Eu crystal with the SiPM epoxied onto one end. The final assembly will be housed in an aluminum can with associated power and readout electronics, in a self-contained unit mounted to the satellite.

The novel CLYC:Ce scintillator was extensively tested in the laboratory and, for the first time, its response to high-energy neutrons was characterized with a beam test at a cyclotron facility.[2] We found that the CLYC:Ce scintillator not only functioned as expected for detecting fast neutrons, but also surprisingly as a spectrometer for internally produced deuterons, tritons, and alpha particles. Figure 5 shows a two-dimensional scatter plot of the pulse shape (time profile of the light pulse) vs pulse height (energy deposited), displaying the discrete banding nature of the different particles produced when the CLYC:Ce is exposed to high-energy neutrons.

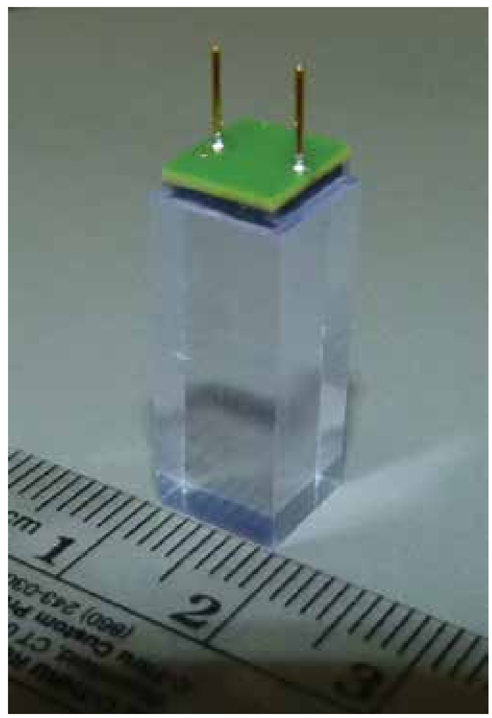

FIGURE 4
The 8 mm × 8 mm × 20 mm SrI:Eu bare crystal with the bonded 6 mm SiPM.

Regardless of the application, understanding the response of these novel scintillation detectors with SiPM light readout devices is of the utmost importance for producing state-of-the-art radiation detection instrumentation for future space flight and for ground-based nuclear security applications. This work will benefit the Navy in radiological tasks both now and in the future.

[Sponsored by the NRL Base Program (CNR funded)]

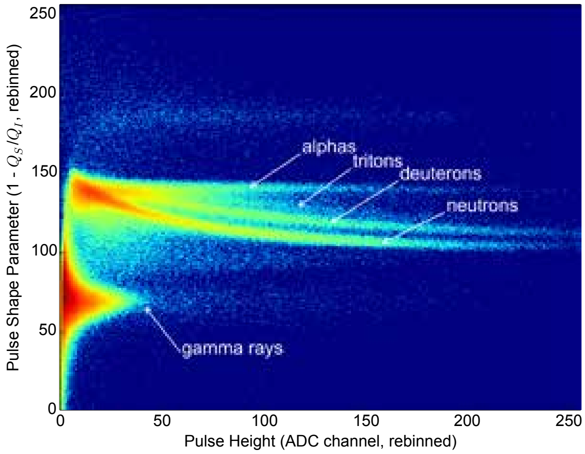

FIGURE 5

The pulse shape vs pulse height two-dimensional scatter plot of the 25.4 mm × 25.4 mm × 25.4 mm CLYC:Ce scintillation detector irradiated by a 60.5 MeV neutron beam. The pulse shape parameter on the y axis is defined as $1 - Q_S/Q_l$, where Q_S and Q_l are the regions encapsulating different parts of the light pulse, selected to optimally exploit differences in the pulse shape, and hence determine the particle type.

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Liquid Lenses for Long-Range Laser Communication

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Introduction: Long-range optical communication in space promises to bring high-speed connectivity across the globe, but only if it can be accomplished affordably. Unfortunately, this type of communication requires extremely precise pointing, which typically translates into very expensive systems. A spacecraft would need to have not only its own attitude control system, but also other mechanisms, like large mechanical beam steering mirrors, to augment those systems to achieve the microradian stability and accuracy that a laser communication system demands. How big is an angle of 1 microradian? If one imagines a long wooden plank stretching the length of a football field, placing a sheet of paper under one end of the plank would create an angle of 1 microradian.

Liquid Lens Technology: Liquid lens technology may provide a solution. The Optilux liquid lens (Optilux Inc., Santa Barbara, CA)[1] is an inexpensive technology with enough capability to provide the precise pointing needed in space and to do so without using large, power-hungry mechanisms. The lens itself is small enough to fit on the tip of one's thumb. It consists of two immiscible liquids sandwiched between two panes of glass that seal the liquids from the ambient environment. The shape of the lensing interface between the two liquids is controlled by four electrodes embedded in the glass (Fig. 6). As voltage across the electrodes is varied, an electromagnetic field across the liquid reshapes this interface and bends the light passing through it. The lens can tip, tilt, and refocus light using less than 1 mW of power and without any moving mechanical components. In other testing, the Optilux liquid lens has been actuated across its operating voltages for millions of cycles, demonstrating high reliability at low power levels.

TVAC Testing: To test whether or not the liquid lens could finely steer a laser in space, the U.S. Naval Research Laboratory (NRL) worked with the liquid lens manufacturer to develop a hermetically sealed lens able to withstand both the extreme vacuum of space and the large temperature differentials of low Earth orbit (LEO). The team then set up an experiment utilizing a thermal-vacuum (TVAC) chamber with a viewing window, and tested the performance of the lens while it endured these harsh conditions for over 3 months (Fig. 7).

Results: Under test, a laser beam was passed into the chamber, off two fold mirrors, through the lens, back out of the chamber, and onto a beam profiler. The beam profiler consisted of a camera to measure the laser beam's shape and location, a translation stage to move the camera along the beam's propagation path, and software to quantify how well the liquid lens was able to hold the beam steady and how finely it was able to steer and refocus the beam. The results showed that the lens was able to hold the laser steady to within 2 microradians and steer the beam with a minimum resolution of 12 microradians (Fig. 8).

After this successful demonstration under space-like conditions, future testing involves first demonstrating the lens as a part of a ground-based optical communication system, before demonstrating the technology on orbit.

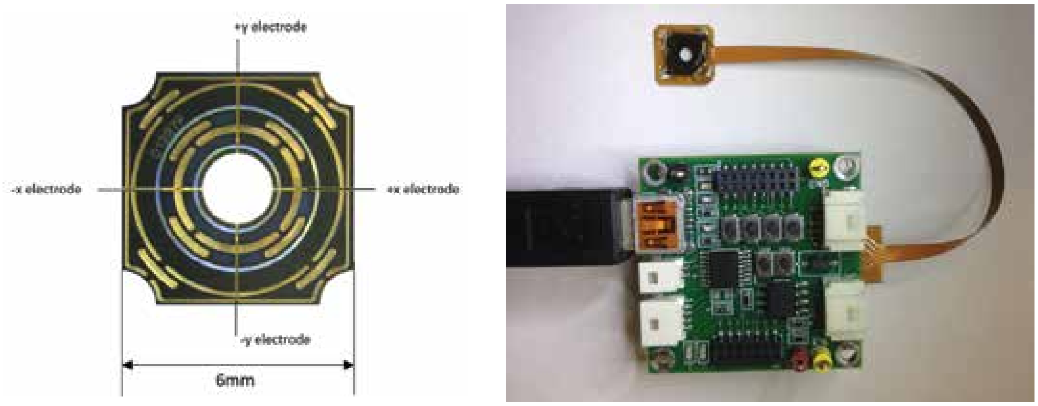

FIGURE 6
The liquid lens controls the lensing of the light by shaping it with an electromagnetic field (left). Applying opposite polarity voltages across the x-axis electrodes tips the laser about the y-axis. Applying opposite polarity voltages across the y-axis electrodes tilts the laser about the x-axis. Applying equal voltages across all four electrodes focuses the laser passing through its center aperture. The liquid lens connects to a driver via flex cable and is controlled using an I2C interface from a PIC microcontroller on board that changes both tilt and focus voltage (right). The lens can be operated using USB to PC connection, direct I2C or push buttons as shown on the demo board. The Optilux liquid lens will correct for vibrations using an optical image stabilization (OIS) algorithm and a low noise gyro.

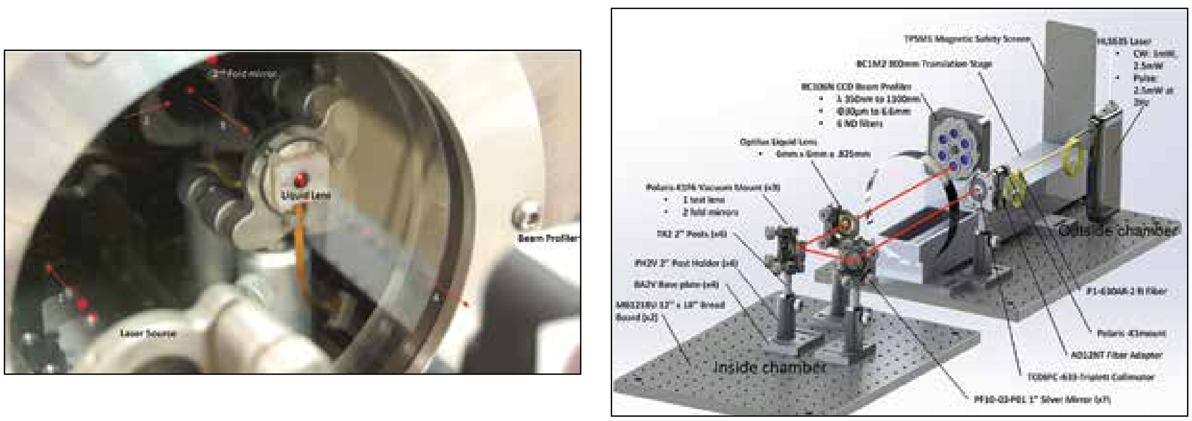

FIGURE 7
To test the liquid lens while under the environmental conditions of low Earth orbit, (left) light from a laser source was (1) passed into the thermal vacuum chamber, (2) bounced off of two fold mirrors, (3) through the liquid lens, and (4) to the beam profiler. The setup is shown in more detail on the right.

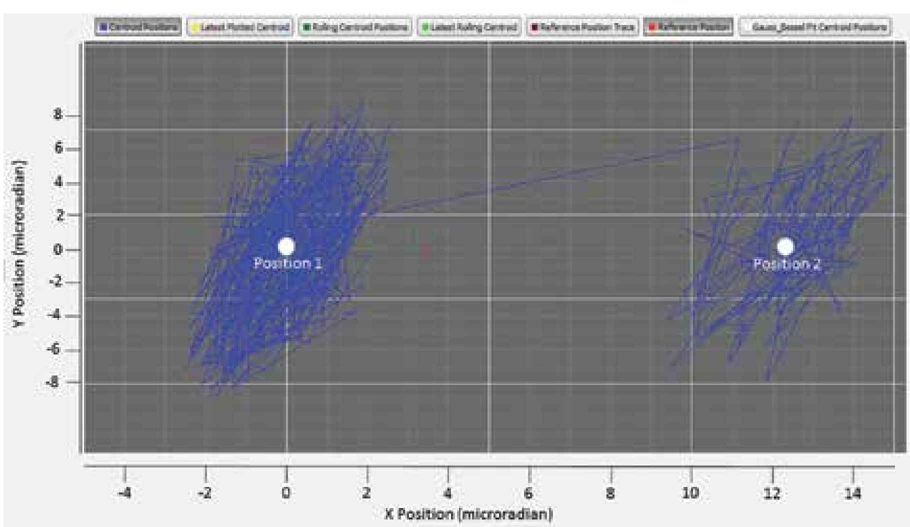

FIGURE 8
Tests results indicate that the liquid lens' minimum step resolution is 12 microradians, the distance between positions 1 and 2. The semi-minor axis of the blue ellipse traced out by the dithering laser indicates that the liquid lens has a pointing stability of 2 microradians.

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Commercial Satellites Boost Maritime Security

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Introduction: The space-based commercial Earth observation marketplace is rapidly emerging and promises to provide unprecedented geospatial information. Some commercial imagery satellites are well suited to provide wide area surveillance for maritime security applications including military, law enforcement, and general maritime monitoring. Accessibility, agility, and area-coverage are important factors for such use; but for imagery products to effectively contribute to a rapidly evolving operational scenario, timeliness of access and delivery is paramount.

Because the present collection cycle for commercial imagery lacks the timeliness demanded by rapidly evolving operations, the U.S. Naval Research Laboratory (NRL) Space Systems Development Department has engineered the Coalition Tactical Awareness and Response, or CTAR, system to access and exploit commercial satellite imagery on operationally relevant timelines. The system tasks and collects imagery from commercial space-based synthetic aperture radar (SAR) and electro-optical (EO) sensors, then processes, exploits, and disseminates tailored, imagery-derived information for the operational need. The system features an expeditionary ground terminal paired with automated detection algorithms developed in NRL's Remote Sensing and Optical Sciences Divisions. This detection information is packed into short textual reports and thumbnail images which can be combined with Automatic Information System signals and directly inserted into a commander's Common Operating Picture systems (COPs).

Architecture: CTAR achieves its timeline by controlling each stage of the Tasking, Collection, Processing, Exploitation, and Dissemination (TCPED) process (Fig. 9). A simple and intuitive software planning tool allows a headquarters user, without extensive knowledge of satellite capabilities, to plan an image of a desired area of interest. The planning tool maps satellite sensor modes and sensing footprint to the user's current needs. The user selects the preferred imaging opportunity and the software generates a task order for submission to the commercial satellite imagery provider.

The most significant contributor to short timelines is CTAR's expeditionary ground terminal. When placed within 1000 miles of the area of interest, the satellite imagery may be downlinked immediately after the image is taken. Collocated with the terminal, the processing software creates an image from the raw satellite data, and the exploitation software finds signatures of interest in the imagery. CTAR has demonstrated the ability to automatically detect ships in the open ocean, but uses similar principles for other observables such as wakes, oil spills, and debris. Each detection is recorded in a text file containing (in the case of ships) location, heading, speed, and length. These text files are sent to the end user's COP, where they are automatically ingested. CTAR has adopted an open-system architecture in which the image processing hardware can host image processing from many commercial satellites provided all agreements and licensing are in place. Likewise, the exploitation hardware can run any algorithm to search for a variety of targets or signatures within the imagery.

Vessel Detection: CTAR hosts different algorithms for the three primary imagery sources, SAR, panchromatic EO, and multispectral EO. CTAR has concentrated on developing automated detection processes. The system can host a variety of detection algorithms for many different observables, but vessel detection is the most developed. The algorithms determine each ship's position on the Earth and create a thumbnail picture of that ship.

CTAR typically employs SAR imagery to cover wide areas of the ocean at low resolution looking for metal vessels on the water (Fig. 10, left). Due to its low resolution, SAR imagery is generally not useful to identify a vessel; but when SAR vessel detections are ingested into the COP, the detections can be sorted by the amount of information already known about those vessels. In some cases, vessels detected by SAR have no previous information within the COP. In that case, the end user may determine which vessels to target with a much higher resolution satellite EO sensor (Fig. 10, right). Panchromatic EO detection uses spatial contrast and is subject to significantly higher rates of false alarm and failure-

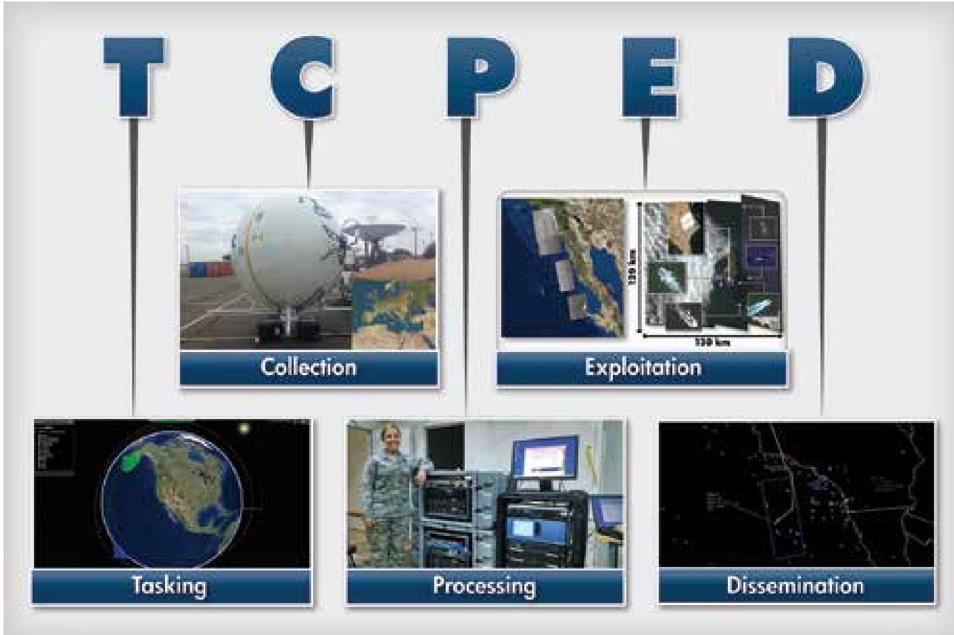


FIGURE 9
Components of the CTAR architecture that make up the TCPED process.

FIGURE 10
SAR image (left) with ship detections indicated as yellow dots and a multi-spectral EO image (right) with insets of interesting content.

to-detect caused by naturally occurring phenomena such as whitecaps and cloud wisps. Multispectral EO detection algorithms exploit the frequency diversity of the image to discriminate natural from man-made phenomena, reducing false positives and increasing probability of detection. In either case, high-resolution detections can be rendered, allowing the end user to classify and perhaps identify the subject vessel. CTAR has proven the utility of orchestrating the low-resolution, wide area detection capability of SAR with the higher-resolution, focused vision of EO. It has accomplished this on timelines quick enough to contribute to decision making in dynamic maritime operations.

Acknowledgments: NRL Space Systems Development Department is responsible for the concept development, system design, integration, testing, and operational demonstrations. NRL Remote Sensing Division contributes to SAR image exploitation, and NRL Optical Sciences Division contributes to EO image exploitation. The authors also acknowledge colleagues J. Warner, K. Bynum, B. Michels, B. Kessel, T. Schirf, B. Gregory, D. Huber, E. Allman, and J. Tugman for their contributions to the program.

[Sponsored by the Department of Homeland Security, U.S. Customs and Border Protection]

CARINA Ionospheric Research Satellites

P. Oppenheimer,[1] P. Bernhardt,[2] G. Creamer,[1] C. Person,[1] and J. Montgomery[1]
[1]*Spacecraft Engineering Department*
[2]*Plasma Physics Division*

Introduction: The U.S. Naval Research Laboratory (NRL) is advancing the state of the art in ionospheric research with direct measurements in the lower thermosphere using a pair of low-cost, rapidly developed spacecraft. The Naval Center for Space Technology in conjunction with the Plasma Physics Division developed the CARINA spacecraft as part of a successful rapid development effort to design, build, and test a pair of spacecraft within one year for under $11M (Fig. 11). The spacecraft are the next evolutionary step in ionospheric research wherein a satellite is put into low low-Earth-orbit (LLEO) in the 150 to 300 km altitude range. Previous space missions have used either suborbital instruments on sounding rockets in the 0 to 1000 km altitude range or orbital sensors on satellites with altitudes above 300 km. The Complex Action of Radio in the Ionosphere for Nonlinear Analysis (CARINA) satellites will explore the lower thermosphere with direct, in situ observations and will be able to isolate the sporadic-E layers below the satellite from the F-region structures above the satellite using radio propagation from ground and space-based radio frequency sources.

FIGURE 11
CARINA flight vehicle during integration and testing phase.

Spacecraft Description: The CARINA satellite is 2.3 m long with a diameter of 0.25 m (Fig. 12). Extending from the back of the aerodynamic structure is a 2.3 m antenna connected to an internal electric field receiver. Attitude control of the satellite is achieved using passive aerodynamic stability via the fins and slender body shape, augmented with internal active momentum control. Nominally, the spacecraft flies into the thermospheric wind to minimize drag using a combination of reaction wheels for pointing control, magnetic torque coils and a magnetometer for wheel momentum management, and redundant star trackers for attitude knowledge. On the body of the spacecraft are antennas for the dual frequency GPS receiver and the telemetry, tracking, and command (TT&C) receiver. Power is provided by primary cell batteries which take up the bulk of the volume inside the satellite. The ram face of the satellite is a stainless steel Langmuir probe biased for ion collection.

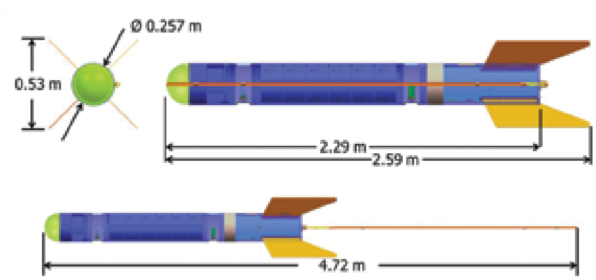


FIGURE 12
CARINA mechanical configurations before (top) and after (bottom) antenna deployment. The Langmuir probe (green) is on the front and the electric field antenna (orange) is deployed in the wake.

Spacecraft Development: In an era in which spacecraft design and development often takes upwards of a decade and hundreds of millions of dollars, the rapid and low-cost CARINA program truly stands out in contrast. A combination of both execution approach and program risk tolerance enabled this prototyping development. The vehicles were built using a combination of space-qualified and commercial off-the-shelf (COTS) instruments. All COTS components went through a rigorous space qualification program. Generally, parts were selected that could be manufactured or procured in 4 months or less. Simplicity was practiced through all aspects of the program (design, integration and test, and operations). For example, the spacecraft has no solar cells, an omnidirectional communications antenna, and a natural, aerodynamically stable "safe mode." Hence, if an error is detected on orbit, the vehicle does not require its sensors and software to point solar arrays at the Sun and antennas to the ground. Ten mission requirements, which focused on the core purpose of the science mission, were the basis of the design. All other requirements were derived and traded within the team to meet the challenging cost and schedule. The design of the vehicle took lessons learned from the low-cost sounding rocket industry to support quick and easy assembly. On larger programs, documentation of the design can cost more than the physical hardware. In contrast, documentation for the CARINA program was limited primarily to log books, photographs, and hardware travelers. The approach on CARINA was to document the design, assembly, and testing performed, and validate the functionality of the subsystems and spacecraft using a small, focused team (averaging only 20 personnel). This allowed for only one layer of management and a single management/system engineering meeting per week. The entire program was executed internal to NRL, including ground and mission operations, resulting in more informal and dynamic interface documentation.

Science Instruments: Three instruments designed to measure the ionosphere from around 200 km altitude are being flown on CARINA. First, the Electric Field Instrument (EFI) connected to the trailing monopole measures electromagnetic and electrostatic waves in the 3 kHz to 13 MHz frequency range. The dynamic range of the EFI is 80 dB with two ranges. The high range detects strong electric fields with maximum strength of 10 V/m. The low range has a peak amplitude of 100 mV/m before saturation.

The second instrument on CARINA is the fixed bias Ram Langmuir Probe (RLP) that measures ion densities in the 10^2 to 10^6 cm^{-3} range. This probe will be sampled at 8 kHz to have a spatial resolution of about 1 km. The RLP data can be acquired continuously over one 24-hour period.

The third instrument is the Orbiting GPS Receiver (OGR) that uses measurements at L1 and L2 to determine the position of the satellite and the integrated electron density or total electron content (TEC) in the F-layer above the satellite. Dual frequency measurements of carrier phase and pseudo-range are processed on the satellite to yield continuous measurements of slant TEC and radio scintillations around the globe along the CARINA orbit.

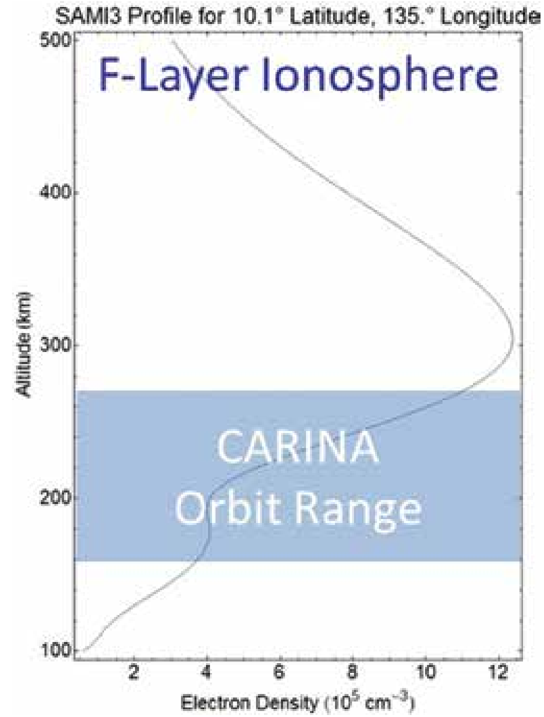


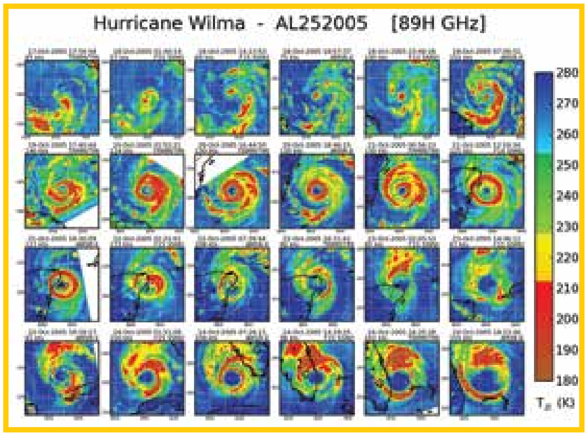
FIGURE 13
Sub-ionsopheric region of the upper atmosphere monitored by the CARINA spacecraft.

Science: The primary science objectives for CARINA are (1) direct observations of the bottomside ionosphere during ionospheric modification experiments, (2) mapping of sporadic-E layer patches by propagation of high frequency signals from ground radio beacons, (3) imaging of the F-region by tomographic and assimilation processing of the in situ plasma densities and GPS TEC observations, and (4) estimation of satellite drag coefficients in the 150 to 300 km altitude range. CARINA provides a unique opportunity for long-term monitoring of the bottom side of the ionosphere (Fig. 13).

[Sponsored by the Department of Defense]

NRL SCIENCE AS ART CONTEST

Marine Meteorology Division Choice



Evolution of Hurricane Wilma

These images diagram the lifecycle of Hurricane Wilma in 2005, the strongest tropical cyclone observed in the Atlantic basin and part of the most active Atlantic hurricane season on record. The rows of pictures were created from a combination of space-borne passive microwave sensors that "see through" cloud tops into the large ice inside the storm. Starting with the left image in the top row, they show the structural change of Wilma from a weak tropical depression through its rapid intensification into the large major hurricane that struck Cancun and south Florida. The top row shows the wrapping of spiral banding and the formation of an "eye" (calm center) with its surrounding "eyewall" (the most intense part of the storm). Multiple eyewall replacement cycles (often associated with strong storms) that relate to fluctuations in intensity can be seen in the second and third rows.

Joshua Cossuth
Marine Meteorology Division

NRL LIFETIME ACHIEVEMENT AWARD

Dr. John Montgomery
Former NRL Director of Research (retired)

Dr. John A. Montgomery was recognized for a distinguished 48-year career at the U.S. Naval Research Laboratory where he helped strengthen national security through the creation of powerful new capabilities for the Department of the Navy and the nation, both as an expert in the area of Electronic Warfare (EW) and as NRL's Director of Research. As a performing engineer, Dr. Montgomery helped revolutionize EW for the Naval Service, the Defense Department, and America's allies by bringing basic research results, from many disciplines, together to field a critical operational system. During his time with the Navy's foremost EW authority, he was responsible for more than 80 systems approved for operational use. One of these was Super Rapid-Blooming Offboard Chaff, the first widespread decoy system applied to all major Navy surface combatants. Other notable systems were: Specific Emitter Identification, selected as the national standard by the National Security Agency; the AN/ALE-50 towed decoy, nicknamed "Little Buddy" by U.S. pilots; and Dragon Eye, an airborne sensor platform that is now on display in the Smithsonian National Air and Space Museum. As NRL's sixth Director of Research, Dr. Montgomery led the Naval Service's corporate laboratory with widely recognized distinction. His success derived from an ability to cultivate and renew a world-class workforce and from a robust emphasis on effective collaborations with universities, industry, and government agencies. His 14-year tenure as Director affirmed, in a powerful way, Thomas Edison's original idea that a government laboratory, working in league with industry, could strengthen national defense through long-term mission-related research and development.

DR. FRED E. SAALFELD AWARD FOR OUTSTANDING LIFETIME ACHIEVEMENT IN SCIENCE

Mr. Peter Wilhelm
Former Director, Naval Center for Space Technology (retired)

This award is the highest scientific award bestowed upon a naval research scientist by the Office of Naval Research and is named in honor of Dr. Fred E. Saalfeld, the Office of Naval Research Executive Director and Technical Director from 1993–2002. Mr. Wilhelm received the award for contributions to the Department of Defense, the Department of the Navy, and the nation over the span of his career in the areas of intelligence, surveillance and reconnaissance, science, design engineering, navigation, and tactical communications. Since the advent of the Space Age, in the late 1950s, Mr. Wilhelm has provided technical expertise and managerial leadership for some 100 scientific and support satellites launched by NRL. He personally oversaw the design, development, and deployment of 48 of these spacecraft, making him one of the most experienced space system engineers in the world today. Among his many contributions are his work on the world's first reconnaissance satellite during the Cold War; the design of the experimental and early satellites that led to the world-changing Global Position System (GPS); the design of the Clementine satellite, which photographed the entirety of the moon's surface and discovered water at its poles; and the design of WindSat, which measures wind speed and direction over the oceans at a resolution that is directly relevant to naval operations. Wilhelm's overall contributions over the past 55 years perhaps will never be surpassed when it comes to space systems.

PRESIDENTIAL EARLY CAREER AWARDS FOR SCIENTISTS AND ENGINEERS (PECASE)

Dr. Colin Joye
Electronics Science and Technology Division

This award is the highest honor bestowed by the federal government on science and engineering professionals in the early stages of their independent research careers. The Presidential Early Career Awards were first introduced by President Clinton in 1996 and continue to be coordinated by the Office of Science and Technology Policy (OSTP) within the Executive Office of the President. The awards are presented each year to highlight the key role the administration places in encouraging and accelerating American innovation to grow our economy and tackle our greatest challenges. Awardees are selected for their pursuit of innovative research at the frontiers of science and technology and their commitment to community service as demonstrated through scientific leadership, public education, or community outreach. Dr. Joye received the award in recognition for "the development of novel microfabrication techniques that revolutionize the construction of vacuum electronic power amplifiers; his demonstration of a record-breaking 220 gigahertz, 60 Watt radio-wave amplifier, enabling millimeterwave imaging and high data rate communications; and for promoting advanced education, mentoring children in the sciences and outreach to orphans around the world."

AMERICAN SOCIETY FOR METALS (ASM) MEDAL FOR THE ADVANCEMENT OF RESEARCH

Dr. Bhatka Rath
Associate Director of Research for Materials Science and Component Technology

The Medal for the Advancement of Research was established in 1943 to honor an executive whose major role is the production, fabrication, or use of materials and to recognize the achievements of members of the materials science and engineering community. Recipients are selected from those that, over a number of years, have been consistent champions for research and development, and by foresight and actions have helped substantially to advance the arts and sciences relating to materials science and engineering. Dr. Rath received the medal for leadership in promoting basic research and advanced exploratory developments in multidisciplinary fields of materials science and engineering and promoting technological innovation for commercial sector and for national security.

ILLINOIS INSTITUTE OF TECHNOLOGY 2015 PROFESSIONAL ACHIEVEMENT AWARD

Dr. Bhatka Rath
Associate Director of Research for Materials Science and Component Technology

The award recognizes outstanding achievement in a professional field and honors the alumni whose achievements have brought distinction to themselves as well as credit to the university. This is one of the highest distinctions the university can bestow upon an alumnus. Dr. Rath was recognized with many honors and awards including the Lifetime Achievement Award from NRL and the Fred E. Saalfeld Award from Office of Naval Research, Department of Defense Distinguished Civilian Service Award from Office of the Secretary of Defense, and the Distinguished Presidential Rank Award.

LABORATORY SCIENTIST OF THE QUARTER AWARD (4QFY15)

Dr. Bradley Ringeisen
Chemistry Division

Dr. Ringeisen was recognized for "extraordinary service to the Department of Defense (DoD) for his distinguished accomplishments in the development and expansion of the applications of three-dimensional (3D) bioprinting using the Navy's patented biological laser printer, or BioLP." He is an internationally recognized leader and pioneer of live cell and organ printing. As a direct result of his leadership and innovative development, Dr. Ringeisen's laboratories at the NRL have been selected to be the focal point for a Defense Health Program supported 3D Bioprinting and Fabrication Consortium — a multiuser facility harboring multiple, diverse bioprinting technologies that will serve as a validation center for DoD-funded bioprinting programs important to soldier health, such as, traumatic brain injury, hearing loss, and eye and cornea surgery. By reaching out to the Walter Reed National Military Medical Center and the Uniformed Services University of the Health Sciences to bridge the NRL bioprinting technology with DoD biomedical researchers and clinicians, Dr. Ringeisen established a consortium of industry, academic, government, and military researchers within a single laboratory facility that supports multiple programs.

SECRETARY OF THE NAVY INNOVATION AWARD AND HONORABLE MENTION

Mr. Daniel Robinson
Tactical Electronic Warfare Division
Dr. Charlie Barron, Ms. Lucy Smedstad, and Ms. Pamela Posey
Oceanography Division

The SECNAV Innovation Awards recognize the top innovators within the Department of Navy and serve as inspiration for the entire workforce to think boldly to solve the most challenging problems. Awards in the eight categories represent a distinguished testament to the outstanding ingenuity and significant accomplishments and professionalism of the Department of Navy workforce. In the category of Outside the Box, Mr. Daniel Robison was named winner for the development of Electronic Warfare Battle Management Software. This category seeks to identify contributions that are cross-cutting and represent a change in thinking. The novel software and system architecture, developed by Robinson, enables for the first time an interconnection between a tactical electronic warfare system and intelligence assets to provide advanced warning critical to defeating modern antiship threats. In the category of Robotics and Autonomous Systems, Dr. Charlie Barron and Ms. Lucy Smedstad received honorable mention for the Glider Observation STrategy (GOST) project. This honor was bestowed to the team for distinguished advances to these emergent and vital fields, and recognized contributions in robotics and autonomous systems within the science and technology community. GOST is an automated system designed to optimize planned waypoints and navigation objectives for unmanned gliders and underwater vehicles (UAVs/UUVs) and allows networking across autonomous platforms. Honorable mention also went to Ms. Pamela Posey in the category of Data Analytics, for the development and demonstration of the Fractures, Leads, and Polynyas Analytic and Forecast Modeling. This award recognizes members of the data savvy workforce that implemented new approaches to using data analytics to improve performance, support decision making, or provide meaningful insight to existing processes. Ms. Posey received this honor for this new innovation that captures and predicts opening of sea ice areas (fractures and leads) and polynyas (unfrozen openings) in Arctic ice by calculating areas of ice convergence and divergence, ice opening rates, ice ridging, and ice shear — an invaluable asset to Naval Arctic operations.

2014 DR. DELORES M. ETTER TOP SCIENTISTS AND ENGINEERS OF THE YEAR AWARD

This award, sponsored by the Assistant Secretary of the Navy for Research, Development and Acquisition, is presented annually to Navy civilian and military personnel who have made significant contributions to their fields and to the Fleet. It is named after former Assistant Secretary of the Navy Dr. Delores Etter, who established the awards in 2006 to recognize these contributions and to promote continued scientific and engineering excellence. More than 35,000 scientists and engineers across the Department of the Navy are eligible. Nominees must have demonstrated exceptional scientific and engineering achievement in their field during the preceding calendar year of the award. Achievements are considered significant when they establish a scientific basis for subsequent technical improvements of military importance, materially improve the Navy's technical capability, and/or materially contribute to national defense.

Top Scientists and Engineers

Plasma Physics Division
Dr. Dmitri Kaganovich
Radar Division
Dr. Geoffrey San Antonio
Optical Sciences Division
Dr. Daniel Gibson
Dr. Michael Stewart
Mr. Kenneth Sarkady
Dr. Gregory Lynn
Mr. Roger Mabe
Dr. Hugo Romero
Mr. David Merritt Cordray

Remote Sensing Division
Dr. Mark Sletten
Electronics Science and Technology Division
Dr. David Abe
Dr. Simon Cooke
Dr. Baruch Levush
Dr. John Pasour
Dr. Boris Feygelson
Materials Science and Technology Division
Dr. James Wollmershauser

DR. ARTHUR E. BISSON PRIZE FOR NAVAL TECHNOLOGY ACHIEVEMENT

Drs. James Doyle, Sue Chen, Eric Hendricks, Richard Hodur, Teddy Holt, Hao Jin, Yi Jin, Jonathan Moskaitis, Melinda Peng, Patrick Reinecke, and Shouping Wang
Marine Meteorology Division

This award honored the team for expertise and innovative scientific work resulting in the rapid development, from basic research to transition to operations, of an innovative and versatile Numerical Weather Prediction system significantly improving the prediction of tropical cyclones — one of the most significant threats to Department of Defense operations in the tropical and mid-latitude ocean areas around the world. The team was named for their achievements in contributing to the improved safety of Navy personnel, DoD assets, and the broader civilian population in coastal regions through their development of the Coupled Ocean/Atmosphere Mesoscale Prediction System for Tropical Cyclones (COAMPS-TC™). Currently, the Joint Typhoon Warning Center (JTWC) and National Hurricane Center (NHC) use COAMPS-TC for forecast guidance for the wind speed intensity of tropical cyclones and to forecast their speed and direction of movement. Because COAMPS-TC showed significant promise in predictive skill, both JTWC and NHC incorporated its products into their official 'Consensus' forecasts in 2012, well before the official model transition date. Improvements are continuing to be made to COAMPS-TC that will ultimately provide more accurate guidance for Department of Defense and U.S. government forecasters.

2015 WASHINGTON ACADEMY OF SCIENCES AWARD FOR ENGINEERING SCIENCES

Dr. Robert Gover
Tactical Electronic Warfare Division

Dr. Gover received this award for "his work on the development, implementation, and application of high-fidelity physics-based digital models for the development of optimized electronic warfare countermeasures against modern anti-shipping cruise missiles." As head of NRL's Systems Analysis Section, he leads a team of 20 scientists, mathematicians, and engineers in performing defense research and development on the susceptibility of naval ships versus radar-guide threat systems. This research involves working closely with the intelligence community on defining threats to Navy surface assets, assessing susceptibility, and developing mitigation strategies.

NUMA MANSON MEDAL

Dr. Jay Boris
Laboratories for Computational Physics and Fluid Dynamics

Established in 1975 by the Institute for the Dynamics of Explosions and Reactive Systems, this award recognizes mature scientists whom are distinguished by lifelong accomplishments elucidating the prominent features of the dynamics of explosions and reactive systems. Dr. Boris plans and leads research on advanced analytical and numerical capabilities and their engineering applications to solve problems vital to the Department of Navy, the Department of Defense, and the nation. He was recognized for "Flux-Corrected Transport (FCT) and Monotone Integrated Large Eddy Simulation (MILES), theoretical and numerical techniques that he developed at NRL. These reactive flow techniques have been instrumental in uncovering key aspects of the dynamics of explosions and reactive systems over the past three decades by scientists at NRL and around the world and have also allowed NRL to develop the instant-response CT-Analyst model for urban defense against airborne weapons mass destruction."

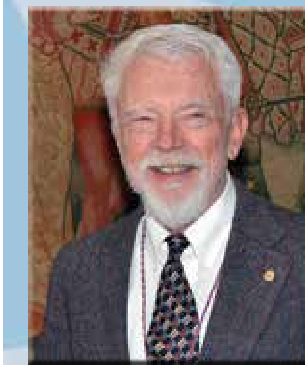
OFFICE OF NAVAL RESEARCH PRIZE FOR AFFORDABILITY

Mr. James Martin, Mr. Jimmy Tagert, Mr. John Wegand, Dr. Erick Iezzi, and Mr. Paul Slebodnick
Chemistry Division

This award honored materials research engineers James Martin, head of the Marine Coatings Science Section, Jimmy Tagert, and John Wegand; research chemist Dr. Erick Iezzi; and physical scientist technician Paul Slebodnick for "significant contributions to an overall reduction in the total ownership costs associated with corrosion control of Navy ships and submarines and achievements in the development and transition of nonskid and topside coatings to the fleet." The team formulated, synthesized, and commercialized topside and nonskid coatings having longer life, high durability, improved weathering resistance and color stability, to replace both legacy nonskid decking and topside coatings. The Navy installs nearly 3.7 million square feet of nonskid coatings per year that typically cost over $56 million annually. At present, the nonskid coatings system has exceeded the one-year flight deck requirement onboard the USS *Theodore Roosevelt* (CVN 71), has outperformed all previous nonskids onboard the USS *Michigan* (SSGN 727), and is still performing well onboard the USS *Bulkeley* (DDG 84). On Navy submarines, this system is the only system ever to pass the submarine nonskid requirements.

PETER HAAS AWARD

Mr. Harold Hughes
Electronics Science and Technology Division



The purpose of the Peter Haas Award is to recognize individuals who have demonstrated outstanding and innovative technical contributions or leadership in the successful development of U.S. hardened military and space systems. Mr. Hughes was recognized for "superior achievement in radiation survivability research and technology by enabling systems hardening through contributions to radiation-hardening successive generations of CMOS [complementary metal-oxide-semiconductor] technologies." At NRL, he has focused on material and device aspects of radiation effects and hardening for over 50 years. His current focus is on hardening deep submicron (less than 100 nanometers) technology nodes for CMOS and CMOS/silicon on insulator integrated circuits, and on advancing neutron detection devices for defense applications. Mr. Hughes has collaborated with industry and academia to develop material and processing solutions for hardening successive generations of integrated circuit technologies. He has also made significant contributions to our understanding of radiation effects mechanisms.

AMERICAN SOCIETY OF MECHANICAL ENGINEERS (ASME) 2015 EXCELLENE IN RESEARCH AWARD

Dr. John Michopoulos
Materials Science and Technology Division

This award reflects the highest honor bestowed to an active researcher by ASME's CIE division. According to the official description by ASME's CIE division, the award recognizes a person for outstanding research contributions in any field associated with the use of computers in engineering and is accompanied by an honorarium. The distinguished award recognizes accomplishments as evidenced by publications, documented testimonials from industry and academic colleagues, and impact on the field of computing in engineering. In particular, it recognizes advances made in the synergistic applications of mechanical engineering and computer science. Dr. Michopoulos was awarded for "outstanding intellectual contributions to the field of computing in engineering." He has earned international acclaim and reputation for research and leadership on many multidisciplinary areas of engineering science and technology. His pioneering work and innovative leadership has resulted in the development of the first autonomous recursive six degrees of freedom (6-DoF) robotic testing system. Designed for the data driven constitutive characterization of anisotropic materials, the robotic material loader recently achieved the highest industrial rates of fully automated multiaxial testing functionality.

JOINT NATO 2014 SCIENTIFIC ACHIEVEMENT AWARD

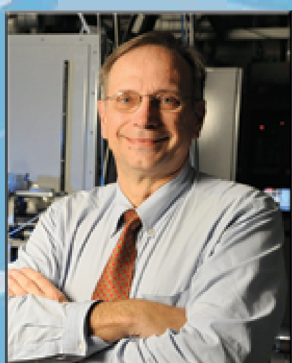
Mr. Robert Gignilliat
Tactical Electronic Warfare Division

Mr. Robert Gignilliat, along with an international task group comprised of 10 member-nations, was awarded the North Atlantic Treaty Organization (NATO), Science and Technology Organization, 2014 Scientific Achievement Award. Head of the Electro-Optic/InfraRed Measurements and Simulation Section at NRL and U.S. delegate to the NATO task group, Mr. Gignilliat and fellow team members of the Sensors and Electronics Technology Panel (SET-144) received the award in recognition and appreciation for outstanding work and significant scientific contribution in the "Mitigation of Ship Electro-Optical Susceptibility against Conventional and Asymmetric Threats." This work focused on several new areas identified as critical in protecting NATO vessels through development of improved understanding and mitigation of ship vulnerabilities to infrared missiles and asymmetric weapons like highly maneuverable small watercraft.

2015 IEEE PLASMA SCIENCE AND APPLICATIONS AWARD

Dr. Alexander Velikovich
Plasma Physics Division

Presented by the Nuclear and Plasma Sciences Society, the award recognizes outstanding contributions to the field of plasma science and engineering, to include plasma dynamics, thermonuclear fusion, plasma sources, relativistic electron beams, laser plasma interactions, diagnostics, and solid-state plasmas. Dr. Velikovich received the award for "for advancing the theory of plasma shocks and hydrodynamics and magneto-hydrodynamics — enabling many-fold increases in both Z-pinch and laser-plasma experimental performance in radiation and fusion applications." Author and co-author of more than 170 publications, with over 2,500 citations, he developed the first analytical theory to calculate the time-dependent growth of compressible Richtmyer-Meshkov (RM) instability in the linear regime and non-linear RM theory explaining reduction of its growth rate for large initial amplitude. Most recently, Dr. Velikovich developed a theory explaining the effect of shock-generated turbulence — discovered in numerical simulations at NRL over a decade ago — on the Rankine-Hugoniot jump conditions. Derived from the laws of mass, momentum and energy, many physical effects, first observed on the Nike krypton fluoride (KrF) laser at NRL, were recreated on both the Nova laser at the Lawrence Livermore National Laboratory, California, and the Omega laser at the Laboratory for Laser Energetics in New York.



2015 SIGMA XI AWARD FOR PURE SCIENCE

Dr. Orest Glembocki
Electronics Science and Technology Division

The Sigma Xi Pure Science Award is presented for distinguished contributions in pure science and to acknowledge exemplary technical success in scientific research at NRL. The award is based on unclassified articles in reviewed scientific publications or on classified reports. Dr. Glembocki was recognized in the Pure Science category for his outstanding contributions in the spectroscopic investigations and fundamental understanding of semiconductor, nanophotonic and metamaterial systems and phenomena.

2015 SIGMA XI AWARD FOR APPLIED SCIENCE

Dr. Steven Bowman
Electronics Science and Technology Division

Winners of this award are selected for their distinguished contribution to pure and applied science during their research at NRL. The awards are given to encourage investigation in pure and applied science and to promote the spirit of scientific research at NRL. Dr. Bowman was awarded in the Applied Science category in recognition of his innovations and discoveries that have greatly advanced the field of solid-state lasers.

2015 SIGMA XI YOUNG INVESTIGATOR AWARD

Dr. Jeremy Robinson
Electronics Science and Technology Division

The Young Investigator Award recognizes researchers in the early stages of their careers whose outstanding contributions best exemplify the ideals of Sigma Xi. The award is given to young investigators for outstanding research performed within 10 years of earning their highest degree and for their ability to communicate that research to the public. Dr. Robinson was recognized for developing graphene-based materials for use in sensing, nanomechanical and nanoelectronics applications.

2016 EXCELLENCE IN TECHNOLOGY TRANSFER AWARD

Interdisciplinary teams from the Laboratories for Computational Physics and Fluid Dynamics and the Chemistry Division

Two interdisciplinary teams at NRL have been awarded the 2016 Excellence in Technology Transfer Award — honoring innovation in technology transfer — by the Mid-Atlantic Region Federal Laboratory Consortium, a regional network of more than 100 federal laboratories and over 350 federal facilities. The NRL teams, comprised of researchers for the NRL-developed technologies Contaminant Transfer Analyst (CT-Analyst®) and Siloxane-Based Non-Skid Coating were presented the awards. CT-Analyst®, developed at the NRL Laboratories for Computational Physics and Fluid Dynamics, is a tool designed to provide first responders with fast and accurate predictions of chemical, biological, and radiological agent transport in urban settings. CT-Analyst® excels at providing immediate results thanks to advanced precomputed plume information databases called Nomografs®. CT-Analyst® was used in a command and control capacity as part of the last two U.S. Presidential Inaugurations and other major national security events. The technology transfer of CT-Analyst® resulted in the delivery of a tool for first responders at the federal, state, local, and international levels. It is currently being used by emergency personnel in Los Angeles, Hamburg in Germany, countrywide in Kuwait, and eventually by Oslo in Norway. The second technology, Siloxane-Based Non-Skid Coating, developed by the NRL Chemistry Division, is a novel two-component siloxane-based non-skid coating for use on the decks of U.S. Navy surface ships. The silicon-based nonskid coating has proven to be more durable, color retentive, and chemical resistant compared to traditional nonskid coatings. The coating was designed for use on the flight decks and walking surfaces of U.S. Navy sea-based assets, such as aircraft carriers, destroyers, and amphibious vehicles, all of which require nonskid to meet numerous performance requirements while preventing slips, trips, and the movement of equipment.

CT-Analyst®

Silicone-Based Non-Skid Coating

DU-CO CERAMICS YOUNG INVESTIGATOR AWARD

Dr. Edward Gorzkowski

Materials Science and Technology Division

Du-Co Ceramics Company established the Young Professional Award through the American Ceramic Society (ACerS) in honor and memory of the late Reldon W. Cooper, who co-founded Du-Co Ceramics in 1949. The annual award is presented to members of ACerS who demonstrate exceptional leadership and service to ceramic society. Dr. Gorzkowski received the award for "outstanding commitment, exceptional leadership, and sustained contributions to his service to ACerS and the ceramics research community." Throughout his young career, Gorzkowski has served on several ACerS committees and awards panels. His service to the society illustrates the diverse spectrum of contributions he has made, ranging from education to development of young professionals, to research.

2016 INTERNATIONAL SCIEITY OF INFORMATION FUSION (ISIF) YOUNG INVESTIGATOR AWARD

Dr. David Crouse

Radar Division

Founded in 1998, ISIF works to advance the field of multi-sensor information fusion and addresses topics related to both active and passive multistatic target localization; tracking; identification; and classification using data from sonar, radar, and electro-optical systems. Presented at the International Conference on Information Fusion in Heidelberg, Germany, the award is granted to candidates no more than 35 years of age to encourage individual effort and to foster increased participation by developing researchers and engineers. Dr. Crouse was presented the award for "contributions to the theory and promulgation of algorithms for multi-sensor multi-target tracking, estimation and data association." The importance of Dr. Crouse's contributions to the field of tracking and data fusion is widely recognized," said Dr. Bruce Danly, superintendent, NRL Radar Division. "This award represents formal acknowledgement of the quality and value of the research and development he performs for the Navy and brings recognition and prestige to the NRL for the important contributions he is making."

AMERICAN SOCIETY OF MECHANICAL ENGINEERS (ASME) 2015 BEST PH.D. THESIS OF THE YEAR AWARD

Dr. John Steuben

Materials Science and Technology Division

Since 2013, the ASME Computers and Information in Engineering (CIE) Division has presented the award in recognition of promising young investigators who authored the best Ph.D. thesis of the year in the area of computers and information in engineering. Dr. Steuben, was awarded the prestigious award for his dissertation entitled "Massively Parallel Engineering Simulations On Graphics Processors: Parallelization, Synchronization, and Approximation." His dissertation examined three computer-aided engineering methods; boundary element method (BEM), discrete element method (DEM), and finite element method (FEM) for particular applications. These three methods are crucial elements of the core research upon which CIE was founded. His work led to a general-purpose computing on graphics processing unit (GPGPU) parallelized BEM solver, a GPGPU parallelized DEM model of icing effects of wind turbine blades incorporating frictional, thermal, and phase change effects (requiring synchronization and parallelization), and a surrogate approximation enhanced FEM approach (parallelization, synchronization and approximation) to solving the inverse material characterization problem for non-isotropic composite materials. including those being tested at NRL.

NAVY MERITORIOUS CIVILIAN SERVICE AWARD

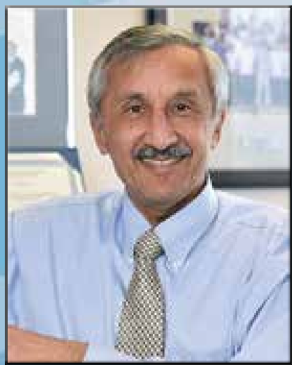
Mr. Scott Browning
Tactical Electronic Warfare Division

The Meritorious Civilian Service Award is the third highest award bestowed by the Navy on its civilian employees. Mr. Browning was recognized for sustained excellent performance pertaining to efforts to develop multiple, diverse breakthrough technologies for classified technical challenges to the Navy and Department of Defense. His research in low observable and counter low observable (LO/CLO) stealth technologies is recognized nationally within the low observables community. His achievements have resulted in major advances in state-of-the-art signature control and LO technologies for naval sea and air platforms. This prestigious award further recognizes Mr. Browning's extraordinary accomplishments toward championing innovative ideas and leading diverse research teams through concept development, successful technology trials, and transition to the end-user. As one of the leading subject matter expert in LO systems, he has provided scientific and managerial advice to the Navy's uniformed and civilian leaders regarding LO technology applicability to meet the needs of the Navy, as well as to other services and Department of Defense leaders. During his tenure at NRL, he led a multidisciplinary team to address a critical national need after the attacks of 9/11; participated on numerous Office of the Secretary of Defense-directed Red Teams to ensure that vital U.S. technology was protected from export; transitioned key technologies into Navy, Air Force, and Defense Advanced Research Projects Agency activities; championed and guided a number of emerging technology thrust areas as Contract Officer Representative and Navy Principal Investigator; developed and tested the first Radar Absorbing Non-Skid for shipboard applications; built the most comprehensive RF measurement/characterization facility within the Department of Defense (of its time); and led the design and procurement of the unique STO Ultra Near Field Electromagnetic Holography characterization facility.

NAVY MERITORIOUS CIVILIAN SERVICE AWARD

Dr. Paul Natishan
Chemistry Division

The Meritorious Civilian Service Award is the third highest award bestowed by the Navy on its civilian employees. Dr. Natishan was recognized for "his outstanding performance and record of scientific achievements and contributions made to the Navy in the field of corrosion science and technology." During his tenure at NRL, he has provided a significant service to the Navy and the nation through an improved scientific understanding of materials in the marine environment. His work in the passivity and passivity breakdown of metals, along with his work in surface modification, has advanced the Navy's understanding of aluminum and stainless steel materials. "Dr. Natishan's breakthroughs in corrosion science have been an immeasurable contribution to the Navy as well as to the world in establishing a more thorough scientific understanding of corrosion phenomena and mitigation measures," said CAPT Mark Bruington, Commanding Officer, NRL. "As an internationally recognized expert in corrosion science, his contributions and achievements have allowed for conventional materials used in many applications for the Navy — operating continuously in a chlorine-laden environment — to be made more resistant to localized corrosion and degradation."



E.O. HULBURT ANNUAL SCIENCE AWARD

Dr. Jasbinder (Jas) Sanghera
Optical Sciences Division

The E.O. Hulburt Science Award was established in December 1955, on the occasion of the retirement of American physicist, Dr. Edward O. Hulburt — appointed the first Director of Research at NRL, January 28, 1949. The establishment of the award expresses, in part, the sincere and high esteem in which Hulburt was held at NRL as well as within the scientific community. The E.O. Hulburt Award is the highest award the NRL Commanding Officer can confer on an NRL civilian employee. Dr. Sanghera was recognized for "his exceptional contributions to basic and applied scientific and technological phenomena, and pioneering the development of novel glasses, ceramics, crystals, thin films, fibers, bulk optics, and devices incorporating these materials. His research has led to the development of new and unique optical materials, solid-state optics, surface physics, laser power transmission and generation, and studies of optical phenomena in a wide variety of materials over an extensive range of wavelengths.

COMMANDING OFFICER'S AWARD IN SECRETARIAL SUPPORT

Ms. Cherie Joyce
Ocean and Atmospheric Science and Technology Directorate

The Commanding Officers Award for Excellence in Secretarial Support was established in 1994 for bestowal by the Commanding Officer on NRL civilian employees in recognition of significant contributions during the most recent full performance appraisal period, through the present time, while working in a secretarial position. Ms. Joyce was presented the award for outstanding performance and professionalism in dealing with numerous challenges and the execution of extraordinary duties in support of the Directorate and the NRL mission. "Ms. Joyce has displayed outstanding proficiency and acumen in the performance of her duties as Executive Secretary to the Associate Director of Research and to the Directorate's Military Deputy, Special Assistant, and the division employees both at the headquarters and those remotely located in Mississippi and California," said Dr. Edward Franchi, Associate Director of Research, Ocean and Atmospheric Science and Technology Directorate. "She has dealt very effectively with a number of extraordinary challenges while performing her normal duties to ensure that the Directorate is most responsive to the needs of the Code 7000 divisions and the Director of Research and Commanding Officer staffs." Her efforts in these additional support roles make important contributions toward the accomplishment of NRL's mission as the corporate laboratory of the Navy and U.S. Marine Corps.

THE *2015 NRL REVIEW* ARTICLE AWARDS

Awards for *NRL Review* articles recognize authors who submit outstanding research articles for this publication. The articles are judged on the relevance of the work to the Navy and Department of Defense, readability to the college graduate level, clearness and conciseness of writing, and the effective use of graphics that are interesting and informative. The following awards were presented for articles that appeared in the *2015 NRL Review*.

Featured Research Article

"Understanding the Relationship between Blast and Traumatic Brain Injury," by Dr. Thomas O'Shaughnessy, Dr. Amit Bagchi, Dr. Siddiq Qidwai (Materials Science and Technology Division), and Dr. Carissa Soto (Center for Bio/Molecular Science and Engineering)

Dr. Thomas O'Shaughnessy, Dr. Amit Bagchi, and Dr. Siddiq Qidwai receive the award for the winning featured research article. Dr. Carissa Soto was not present.

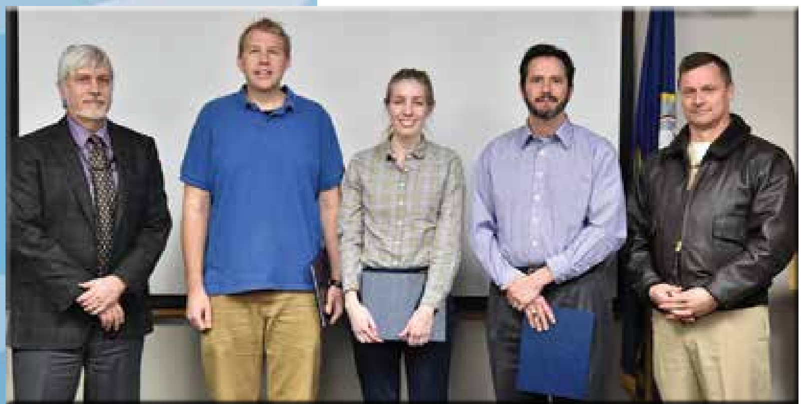
Directorate Awards for Scientific Articles

Systems Directorate
"Adaptive Transmit Nulling with MIMO Radar," by Dr. Tegan Webster, Mr. Thomas Higgins, and Dr. Aaron Shackelford (Radar Division)

Materials Science and Component Technology Directorate
"Understanding and Preventing Lithium-ion Battery Fires," by Dr. Corey Love, Dr. Olga Baturina, Dr. Karen Swider-Lyons (Chemistry Division), and Dr. Michelle Johannes (Materials Science and Technology Division)

Ocean and Atmospheric Science and Technology Directorate
"UAS Impact on Marine Atmospheric Boundary Layer Forecasts," by Dr. James Doyle, Dr. Teddy Holt, Dr. David Flagg, Dr. Clark Amerault, Mr. Bernard Cook, Ms. Tracy Haack, Dr. Jason Nachamkin, Dr. Patricia Pauley, and Dr. Daniel Tyndall (Marine Meteorology Division)

Naval Center for Space Technology
"High Power Density Actuation for Robotics," by Mr. Jordan Schlater, Mr. Carl Henshaw, Dr. Joseph Hays, Mr. Michael Osborn, and Mr. Joshua Geating (Spacecraft Engineering Department)



Dr. Thomas Higgins, Dr. Tegan Webster, and Dr. Aaron Shackelford, receive the award for the winning article from the Systems Directorate.

Dr. Michelle Johannes, Dr. Corey Love, and Dr. Karen Swider-Lyons receive the award for the winning article from the Materials Science and Component Technology Directorate. Dr. Olga Baturina was not present.

Dr. Bernard Cook, Dr. Patricia Pauley, Dr. Jason Nachamkin, Dr. Clark Amerault, Dr. David Flagg, and Dr. Teddy Holt receive the award for the winning article from the Ocean and Atmospheric Science and Technology Directorate. Dr. James Doyle, Ms. Tracy Haack, and Dr. Daniel Tyndall were not present.

Mr. Joshua Geating, Dr. Carl Henshaw, Dr. Joseph Hays, and Mr. Michael Osborn receive the award for the winning article from the Naval Center for Space Technology. Mr. Jordan Schlater was not present.

ALAN BERMAN RESEARCH PUBLICATION AND NRL EDISON (PATENT) AWARDS

The Annual Research Publication Awards Dinner (ARPAD) was established in 1968 to recognize the authors of the best NRL publications each year. These awards not only honor individuals for superior scientific accomplishments in the field of naval research, but also seek to promote continued excellence in research and in its documentation. In 1982, the name of this award was changed to the Alan Berman Research Publication Award in honor of its founder. Of the 202 papers nominated for the 2016 awards, 35 were selected for recognition. They represent 168 authors.

NRL also recognizes patents as part of its annual publication awards program. The NRL Edison (Patent) Awards were established in 1991 to recognize NRL employees for outstanding patents issued to NRL by the U.S. Patent and Trademark Office during the preceding calendar year. The awards recognize significant NRL contributions to science and engineering, as demonstrated by the patent process, that are perceived to have the greatest potential benefit to the country. Of the 106 patents considered for 2016, 3 were selected, representing 11 inventors and 3 patent attorneys.

PUBLICATION AWARDS

Radar Division

Passive Multistatic Radar Experiment using WiMAX Signals of Opportunity.
Part 1: Signal Processing and Part 2: Multistatic Velocity Backprojection
Dr. Thomas Higgins, Dr. Tegan Webster, and Dr. Eric Mokole

A Parameterized Pattern-Error Objective for Large-Scale Phase-Only Array Pattern Design
Dr. Dan Scholnik

Information Technology Division

Detection of Gravitational Frame Dragging Using Orbiting Qubits
Dr. Marco Lanzagorta-Saldana and Dr. Marcelo Salgado

Indelible Mark Modulations for Jam Resistance
Dr. Andrew Robertson and Mr. Joseph Molnar

Optical Sciences Division

Meausring Vibrational Motion in the Presence of Speckle Using Off-Axis Holography
Mr. L. Brandon Redding, Mr. Allen Davis, Mr. Clay Kirkendall, and Dr. Anthony Dandridge

Infrared Glass-Based Negative-Curvature Anti-Resonant Fibers
Fabricated through Extrusion
Dr. Raphael Gattass, Dr. Jasbinder Sanghera, Dr. Daniel Gibson, Dr. Vinh Nguyen, Dr. Shyam Bayya, Dr. Leslie Shaw, Mr. Daniel Rhonehouse, Mr. Collin McClain, Dr. Rajesh Thapa, Dr. R. Joseph Weiblen, and Dr. Curis Menyuk

Tactical Electronic Warfare Division

Generalized Transmitter Compensation of Frequency Dependent I/Q Imbalance
Dr. Kevin Lorenz, Mr. Joel Goodman, Dr. Nixon Pendergrass, and Dr. George Stantchev

Arbitrary Transformation of Radiation Patterns Using a Spherical Impendence Metasurface
Dr. Brian Raeker and Mr. Scott Rudolph

Laboratories for Computational Physics and Fluid Dynamics

Observational Signatures of Coronal Loop Heating and Cooling Driven by Footpoint Shuffling
Dr. Russell Dahlburg, Dr. Brian Taylor, Dr. Harry Warren, Dr. Giorgio Einaudi, Dr. Ignacio Ugarte-Urra, Dr. Antonio Rappazzo, and Dr. Marco Velli

Chemistry Division

Sequence Basis of Barnacle Cement Nanostructure is Defined by Proteins with Silk Homology
Dr. Christopher R. So, Dr. Kenan P. Fears, LCDR Jenifer M. Scancella, Dr. Kathyrn J. Wahl, Dr. Dagmar H. Leary, Dr. Zheng Wang, Dr. Jinny L. Liu, Dr. Christopher Spillmann, Ms. Beatriz Orihuela, and Dr. Dan Rittschof

Factors Affecting Electrochemical Stability in the Silver-Silver Halide-Electrolyte System
Dr. Steven Policastro, Dr. Christine Sanders, Dr. Brandice Weathers, Dr. Nicole Tailleart, Ms. Elizabeth Hogan, Ms. Theresa Newbauer, and Ms. Sarah Eppard

Materials Science and Technology Division

Origin and Control of Blinking in Quantum Dots
Dr. Alexander Efros and Dr. David Nesbitt

Disordered RuO_2 Exhibits Two Dimensional, Low-Mobility Transport and a Metal-Insulator Transition
Dr. Michael Osofsky, Ms. Kristin Charipar, Dr. Konrad Bussmann, Dr. Christopher Chervin, Dr. Debra Rolison, Dr. Clifford Krowne, and Dr. Irina Pala

Plasma Physics Division

Laser-Accelerated Ions from a Shock-Compressed Gas Foil
Dr. Michael Helle, Dr. Daniel Gordon, Dr. Dmitri Kaganovich, Dr. John Palastro, Dr. Yu-Hsin Chen, and Dr. Antonio Ting

Numerical Simulations of the Ablative Rayleigh-Taylor Instability in Planar Inertial-Confinement-Fusion Targets Using the FastRad3D Code
Dr. Jason Bates, Dr. Andrew Schmitt, Dr. Max Karasik, and Dr. Steven Zalesak

Electronics Science and Technology Division

FRET from Multiple Pathways in Fluorophore-Labeled DNA
Dr. Joseph Melinger, Dr. Mario Ancona, Dr. Paul Cunningham, Dr. Susan Buckhout-White, Dr. Ellen Goldman, Dr. Christopher Spillmann, Dr. Igor Medintz, and Dr. Ani Khachatrian

Frequency-Selective Limiters Utilizing Contiguous-Channel Double Multiplexer Topology
Dr. Eric Naglich and Dr. Andrew Guyette

Center for Bio/Molecular Science and Engineering

Rise of the Charge Transfer Plasmon: Programmable Concatenation of Conductively Linked Gold Nanorod Dimers
Dr. Jake Fontana, Dr. Jawad Naciri, Dr. Banahalli Ratna, Mr. Nicholas Charipar, Dr. Alberto Piqué, and Dr. Steven Flom

Photo-Enhanced Hydrolysis of Bis(4-Nitrophenyl) Phosphate Using Cu(II) Bipyridine-Capped Plasmonic Nanoparticles
Dr. Scott Trammell, Dr. Brett Martin, Mr. Martin H. Moore, Dr. Jake Fontana, Ms. Rafaela Nita, Ms. Somayeh Talebzadeh, and Dr. Andrew Knight

Acoustics Division

Generation of Topologically Diverse Acoustic Vortex Beams Using a Compact Metamaterial Aperture
Dr. Christina Naify, Dr. Charles Rohde, Dr. Theodore Martin, Dr. Michael Nicholas, Dr. Matthew Guild, and Dr. Gregory Orris

Evidence for Spin Glass Ordering Near the Weak to Strong Localization Transition in Hydrogenated Graphene
Dr. Bernard Matis, Dr. Brian Houston, and Dr. Jeffrey Baldwin

Remote Sensing Division

Maritime Signature Correction with the NRL Multichannel SAR
Dr. Mark Sletten, Mr. Steven Menk, Dr. Jakov Toporkov, Dr. Robert Jansen, and Dr. Luke Rosenberg

A Multi-Platform Investigation of Midlatitude Sporadic *E* and Its Ties to *E-F* Coupling and Meteor Activity
Dr. Joseph Helmboldt

Oceanography Division

Low-Frequency Currents from Deep Moorings in the Southern Bay of Bengal
Dr. Hemantha Wijesekera, Dr. William Teague, Dr. David Wang, Dr. Ewa Jarosz, Dr. Tommy Jense, Dr. S.U.P. Jinadasa, Dr. H.J.S. Fernando, and Dr. Zachary Hallock

Ocean Processes Underlying Surface Clustering
Dr. Gregg Jacobs, Dr. Timothy Campbell, Dr. Travis Smith, Ms. Kacey Edwards, Mr. Brent Bartels, Dr. Helga Huntley, Dr. A. Denny Kirwan, Jr., and Dr. Bruce Lipphardt, Jr.

Marine Geosciences Division

The Unsteady Hydrodynamic Force during the Collision of Two Spheres in a Viscous Fluid
Dr. Julian A. Simeonov

Bayesian Hindcast of Acoustic Transmission Loss in the Western Pacific Ocean
Dr. Margaret Palmsten and Dr. Josette P. Fabre

Marine Meteorology Division

Impact of Swell on Air-Sea Momentum Flux and Marine Boundary Layer under Low-Wind Conditions
Dr. Qingfang Jiang, Dr. Shouping Wang, Dr. James Doyle, Dr. Peter Sullivan, and Dr. Linwood Vincent

Daytime Cirrus Cloud Top-of-the-Atmosphere Radiative Forcing Properties at a Midlatitude Site and Their Global Consequences
Dr. James Campbell, Dr. Simone Lolli, Dr. Jasper Lewis, Dr. Yu Gu, and Dr. Ellsworth Welton

Space Science Division

Dynamics of Orographic Gravity Waves Observed in the Mesosphere over the Auckland Islands during the Deep Propagating Gravity Wave Experiment (DEEPWAVE)
Dr. Stephen Eckermann, Dr. James Doyle, Dr. Dave Broutman, Dr. Jun Ma, Dr. Pierre-Dominique Pautet, Dr. Michael Taylor, Dr. Katrina Bossert, Dr. Bifford Williams, Dr. David Fritts, and Dr. Ronald Smith

Comparative Ionosphere Impacts and Solar Origins of Nine Strong Geomagnetic Storms in 2010–2015
Dr. Brian Wood, Dr. Judith Lean, Dr. Sarah E. McDonald, and Dr. Yi-Ming Wang

Space Systems Development Department

On the Mitigation of Solar Index Variability for High Precision Orbit Determination in Low Earth Orbit
Mr. John Warner and Ms. Annie Lum

Impacts of GNSS Position Offsets on Global Frame Stability
Dr. Jake Griffiths and Dr. James Ray

Spacecraft Engineering Department

Hypersonic Waverider Stream Surface Actuation for Variable Design Point Operation
Mr. Jesse Maxwell

Spatial Density Maps from a Debris Cloud
Dr. Liam Healy, Mr. Scott Kindl, and Mr. Christopher Binz

NRL EDISON (PATENT) AWARDS

Extraction of Carbon Dioxide and Hydrogen from Seawater and Hydrocarbon Production Therefrom
Dr. Dennis Hardy, Dr. Heather Willauer, Dr. Frederick Williams, LCDR Felice DiMascio, CAPT M. Kathleen Lewis, and Rebecca Forman

Full Head Surrogate with Live Neurons for Helmet Testing and Evaluation
Dr. Thomas O'Shaughnessy, Dr. Ryan McCulloch, Dr. Amit Bagchi, Dr. Kirth Simmonds, and Mr. Roy Roberts

Battery Health Monitoring System and Method
Dr. Corey Love, Dr. Karen Swider-Lyons, and Mr. Richard Bis

NRC/ASEE POSTDOCTORAL RESEARCH PUBLICATION AWARDS

Chemistry Division

Modified Relaxation Dynamics and Coherent Energy Exchange in Coupled Vibration-Cavity Polariton
Adam D. Dunkelberger, Bryan T. Spann, Kenan P. Fears, Blake S. Simpkins, and Jeffrey C. Owrutsky

Electronics Science and Technology Division

Aspect-Ratio Driven Evolution of High-Order Resonant Modes and Near-Field Distributions in Localized Surface Phonon Polariton Nanostructures
Chase T. Ellis, Joseph G. Tischler, Orest J. Glembocki, Francisco J. Bezares, Alexander J. Giles, Loretta M. Shirey, Jeffrey C. Owrutsky, Joshua D. Caldwell, Richard Kasica, and Dmitry N. Chigrin

Imaging of Anomalous Internal Reflections of Hyperbolic Phonon-Polaritons in Hexagonal Boron Nitride
Alexander J. Giles, Siyuan Dai, Orest J. Glembocki, Andrey V. Kretinin, Zhiyuan Sun, Chase T. Ellis, Joseph G. Tischler, Takashi Taniguchi, Kenji Watanabe, Michael M. Fogler, Kostya S. Novoselov, Dmitri N. Basov, and Joshua D. Caldwell

Silicon Vacancy Center in 4H-SiC: Electronic Structure and Spin-Photon Interfaces
Oney O. Soykal, Pratibha Dev, and Sophia E. Economou

Center for Bio/Molecular Science and Engineering

Lipid Raft-Mediated Membrane Tethering and Delivery of Hydrophobic Cargos from Liquid Crystal-Based Nanocarriers
Okhil K. Nag, Jawad Naciri, Eunkeu Oh, Christopher M. Spillmann, and James B. Delehanty

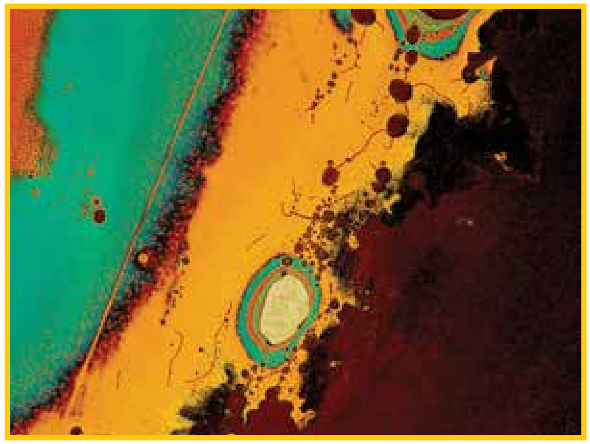
Protecting Enzymatic Function through Directed Packaging into Bacterial Outer Membrane Vesicles
Nathan J. Alves, Kendrick B. Turner, Igor L. Medintz, and Scott A. Walper

Acoustics Division

Aerogel as a Soft Acoustc Metamaterial for Airborne Sound
Matthew D. Guild, Victor M. Garcia-Chicano, Jose Sanchez-Dehesa, Theodore P. Martin, David C. Calvo, and Gregory J. Orris

Programs for Professional Development

NRL SCIENCE AS ART CONTEST
Space Science Division Choice



Nanoscience Meets Modern Art

This optical micrograph shows a thin layer of silicon oxide and nitride sandwiched between two semi-transparent metal mirrors. The depicted structure is a Fabry-Pérot optical filter, a type of thin-film interference filter used in various optical systems. Thin-film interference is a natural phenomenon in which light waves reflected by the upper and lower boundaries of a thin film interfere with one another to form a new wave. A common example of this phenomenon is an oil film on water, as with the colorful interference pattern created by gasoline or diesel fuel on wet asphalt. The colorful interference pattern is caused by light reflected from the top and bottom boundaries of the thin film of oil.

Marc Christophersen
Space Science Division

PROGRAMS FOR NRL EMPLOYEES

The NRL Human Resources Office (HRO) supports and provides traditional and alternative methods of training for employees. NRL employees are encouraged to develop their skills and enhance their job performance so they can meet the future needs of NRL and enhance their own personal growth.

One common study procedure is for employees to work full time at the Laboratory while taking job-related courses at universities and schools local to their job site. The training ranges from a single course to undergraduate, graduate, and postgraduate course work. Tuition for training is paid by NRL. The formal programs offered by NRL are described here.

LONG-TERM TRAINING AND DEVELOPMENTAL PROGRAMS

The **Advanced Graduate Research Program** enables selected professional employees to pursue collaborative research in their own field or a related field on a full-time basis for up to one year at an institution or research facility of their choice without the loss of pay or benefits. NRL pays all travel and moving expenses for the employee. Criteria for eligibility include professional stature consistent with the applicant's opportunities and experience, the ability and special aptitude for advanced training, and acceptance by the facility selected by the applicant. The program is open to employees who have completed six years of Federal service, four of which have been at NRL.

The **Edison Memorial Graduate Training Program** enables employees to pursue graduate-level work that may lead to a graduate degree at a local university. Participants in this program normally work 24 hours per week at the work site, while carrying an appropriate academic load of either graded, credited classes or dissertation research credits. The criteria for eligibility include a minimum of one year of service at NRL, a bachelor's degree in an appropriate field, professional stature consistent with the applicant's opportunities and experience, and the ability and special aptitude for advanced training.

The **Select Graduate Training Program** develops employees of exceptional talent by assisting them in full-time graduate study that may lead to the acquisition of a graduate degree at a facility of their choice within the continental United States. To be eligible for this program, employees must possess at least a bachelor's degree in an appropriate field, have completed at least one full year of service at NRL, and have demonstrated ability and aptitude for advanced training. Students accepted into this program receive one-half of their salary and one-half of their benefits. NRL pays for tuition and travel expenses.

The **Naval Postgraduate School (NPS)**, located in Monterey, California, provides graduate programs to enhance the technical preparation of Naval officers and civilian employees who serve the Navy in the fields of science, engineering, operations analysis, and management. This program enables employees to pursue full-time graduate studies that may lead to the completion of a graduate degree. Thesis work will be accomplished at NRL. To be eligible for this program, employees must possess at least a bachelor's degree in an appropriate field and must have maintained at least a 3.0 GPA in undergraduate course work or previous graduate studies. Employees must also have completed at least two full years of service at NRL, have demonstrated the ability and aptitude for advanced training, and have professional stature consistent with the applicant's opportunities and experience. Participants in the NPS program will continue to receive full pay and benefits during their periods of study. NRL also pays for tuition and travel expenses.

In addition to NRL and university offerings, applications may be submitted for a number of noteworthy Navy developmental programs. These and other fellowship programs are grade-specific and the courses vary in length. A few examples of these opportunities are the **Aspiring Leader Program (ALP)**, **Defense Civilian Emerging Leader Program (DCELP)**, **Executive Leadership Development Program (ELDP)**, and the **Defense Senior Leader Development Program (DSLDP)**. Announcements for these programs are posted on Pipeline (NRL's intranet) as schedules are published.

CONTINUING EDUCATION

Undergraduate and graduate courses offered at local colleges and universities may be subsidized by NRL for employees interested in improving their skills and keeping abreast of current developments in their fields.

NRL offers **short courses** to all employees in a number of fields of interest including administrative subjects and supervisory and management techniques. Laboratory employees may also attend these courses at nongovernment facilities. HRO advertises training opportunities on Pipeline, the HRO website, and in the email newsletter *HRO Highlights*.

For further information on any of the Long-Term Training, Leadership Development, and Continuing Education programs, contact the Employee Development and Management Branch (Code 1840) at (202) 767-8306 or via email at Training@hro.nrl.navy.mil.

The **Scientist-to-Sea Program (STSP)** provides opportunities for Navy R&D laboratory/center personnel to go to sea to gain first-hand insight into operational factors affecting system design, performance, and operations on a variety of ships. NRL is a participant in the program. When these opportunities become available from the Office of Naval Research (ONR), NRL divisions are informed to nominate candidates. For further information, contact (202) 404-2701.

PROFESSIONAL DEVELOPMENT

NRL has several programs, professional society chapters, and informal clubs that enhance the professional growth of employees. Some of these are listed below.

The NRL chapter of **Women In Science and Engineering (WISE)** was established to address current issues concerning the scientific community of women at NRL such as networking, funding, work-life satisfaction, and effective use of our resources. We address these issues by empowering members through the establishment of a supportive and constructive network that serves as a sounding board to develop solutions that address said issues, and then serve as a platform in which members work together to implement solutions. Recently, the NRL chapter of WISE has hosted a women in science and engineering professional career development panel, annual Vision of the Lab presentation, an NRL Research Highlights fast-paced seminar series highlighting cutting-edge research from across the laboratory, and informal Brown Bag lunches. Membership is open to all employees. For more information, contact (202) 404-3050.

Sigma Xi, The Scientific Research Society, encourages and acknowledges original investigation in pure and applied science. It is an honor society for research scientists. Individuals who have demonstrated the ability to perform outstanding research are elected to membership in local chapters. The NRL Edison Chapter, comprising approximately 200 members, recognizes exceptional research by presenting annual awards in pure and applied science to two outstanding NRL staff members per year. In addition, an award seeking to reward rising stars at NRL is presented annually through the Young Investigator Award. The chapter also sponsors several lectures per year at NRL on a wide range of topics of general interest to the scientific and DoD community. These lectures are delivered by scientists from all over the world. The highlight of the Sigma Xi Lecture Series is the Edison Memorial Lecture, which traditionally is given by an internationally distinguished scientist. Contact (202) 767-0351.

The **NRL Mentor Program** was established to provide an innovative approach to professional and career training and an environment for personal and professional growth. It is open to permanent NRL employees in all job series and at all sites. Mentees are matched with successful, experienced colleagues having more technical and/or managerial experience who can provide them with the knowledge and skills needed to maximize their contribution to the success of their immediate organization, to NRL, to the Navy, and to their chosen career fields. The ultimate goal of the program is to increase job productivity, creativity, and satisfaction through better communication, understanding, and training. NRL Instruction 12400.1B provides policy and procedures for the program. For more information, please email mentor@hro.nrl.navy.mil or call (202) 767-8324.

Employees interested in developing effective self-expression, listening, thinking, and leadership potential are invited to join the NRL Forum Toastmasters Club, a chapter of **Toastmasters International**. Members of this club possess diverse career backgrounds and talents and learn to communicate not by rules but by practice in an atmosphere of understanding and helpful fellowship. NRL's Commanding Officer and Director of Research endorse Toastmasters. Contact (202) 404-4670.

The **Department of the Navy Civilian Employee Assistance Program (DONCEAP)** provides confidential assessment, referral, and short-term counseling for employees (or their eligible family members) regarding personal concerns to help avoid adversely affecting job performance. Types of personal concerns may include challenging relationships (at work or at home); dealing with stress, anxiety, or depression; grief and loss; or substance abuse. The DONCEAP also provides work/life referral services such as live or on-demand webinars; discussion groups; and advice on parenting, wellness, financial and legal issues, education, and much more. Contact (844) 366-2327 or visit http://donceap.foh.hhs.gov.

EQUAL EMPLOYMENT OPPORTUNITY (EEO) PROGRAMS

Equal employment opportunity (EEO) is a fundamental NRL policy for all employees regardless of race, color, national origin, sex, religion, age, physical or mental disability, or genetic information. The NRL EEO Office is a service organization whose major functions include counseling employees in an effort to resolve employee/management conflicts, processing formal discrimination complaints and requests for reasonable accommodation, providing EEO training, and managing NRL's MD-715 and affirmative employment recruitment programs. The NRL EEO Office is also responsible for sponsoring special-emphasis programs to promote awareness and increase sensitivity and appreciation of the issues or the history relating to females, individuals with disabilities, and minorities. Contact the NRL Deputy EEO Officer at (202) 767-8390 for additional information on programs or services.

OTHER ACTIVITIES

The award-winning **Community Outreach Program**, directed by the Public Affairs Section of the NRL Strategic Communications Office, fosters programs that benefit students and other community citizens. Employee volunteers assist with and judge science fairs, give lectures, provide science demonstrations and student tours of NRL, and serve as tutors, mentors, coaches, and classroom resource teachers. The program sponsors student tours of NRL and an annual holiday party for neighborhood children in December. Through the program, NRL has active partnerships with several District of Columbia public schools. Contact (202) 767-2541.

In 2015, the Community Outreach Program was expanded to include a coordinated **STEM Program**. In response to the increasing national priority being placed on STEM education, NRL is bolstering its already robust educational outreach to higher education institutions to include more K–12 initiatives. The robotics activities that have been sponsored at the high school level have been extended down into a middle school with plans to include additional middle schools in FY16. As part of its elementary school tutoring program, NRL conducted a pilot activity in which several students designed and constructed a payload and launched it on a high altitude balloon. These new K–12 initiatives are focused in NRL's Anacostia neighborhood of Washington, D.C. and on schools that cater to military families.

Other programs that enhance the development of NRL employees include sports groups and the **Amateur Radio Club**. The **NRL Fitness Center** at NRL-DC, managed by Naval Support Activity Washington Morale, Welfare and Recreation (NSAW-MWR), houses a fitness room with treadmills, bikes, ellipticals, step mills, and a full strength circuit; a gymnasium for basketball, volleyball, and other activities; and full locker rooms. The Fitness Center is free to NRL employees and contractors. Various exercise classes are offered for a nominal fee. NRL employees are also eligible to participate in all NSAW-MWR activities held on Joint Base Anacostia–Bolling and Washington Navy Yard, less than five miles away.

PROGRAMS FOR NON-NRL EMPLOYEES

Several programs have been established for non-NRL professionals. These programs encourage and support the participation of visiting scientists and engineers in research of interest to the Laboratory. Some of the programs may serve as stepping-stones to Federal careers in science and technology. Their objective is to enhance the quality of the Laboratory's research activities through working associations and interchanges with highly capable scientists and engineers and to provide opportunities for outside scientists and engineers to work in the Navy laboratory environment. Along with enhancing the Laboratory's research, these programs acquaint participants with Navy capabilities and concerns and may provide a path to full-time employment.

POSTDOCTORAL RESEARCH ASSOCIATESHIPS

Every year, NRL hosts several postdoctoral research associates through the National Research Council (NRC) and American Society for Engineering Education (ASEE) postdoctoral associateship and fellowship programs. These competitive positions provide postdoctoral scientists and engineers the opportunity to pursue research at NRL in collaboration with NRL scientists and engineers. Research associates are guest investigators, not employees of NRL.

NRL/NRC Cooperative Research Associateship Program: The National Research Council conducts a national competition to recommend and make awards to outstanding scientists and engineers at recent postdoctoral levels for tenure as guest researchers at participating laboratories. The objectives of the NRC program are (1) to provide postdoctoral scientists and engineers of unusual promise and ability opportunities for research on problems, largely of their own choice, that are compatible with the interests of the sponsoring laboratories and (2) to contribute thereby to the overall efforts of the Federal laboratories. The program provides an opportunity for concentrated research in association with selected members of the permanent professional laboratory staff, often as a climax to formal career preparation.

NRL/NRC Postdoctoral Associateships are awarded to persons who have held a doctorate less than five years at the time of application, and are made initially for one year, renewable for a second and possible third year. Information and applications may be found at http://www.national-academies.org/rap. To contact NRL's program coordinator, call (202) 767-8323 or email nrc@hro.nrl.navy.mil.

NRL/ASEE Postdoctoral Fellowship Program: The ASEE program is designed to significantly increase the involvement of creative and highly trained scientists and engineers from academia and industry in scientific and technical areas of interest and relevance to the Navy. Fellowship awards are based upon the technical quality and relevance of the proposed research, recommendations by the Navy laboratory, academic qualifications, reference reports, and availability of funds.

NRL/ASEE Fellowship awards are made to persons who have held a doctorate for less than seven years at the time of application, and are made for one year, renewable for a second and possible third year. Information and applications may be found at http://www.asee.org/nrl/. To contact NRL's program coordinator, call (202) 767-8323 or email asee@hro.nrl.navy.mil.

FACULTY MEMBER PROGRAMS

The **Office of Naval Research Summer Faculty Research and Sabbatical Leave Program** provides for university faculty members to work for ten weeks (or longer, for those eligible for sabbatical leave) with professional peers in participating Navy laboratories on research of mutual interest. Applicants must hold a teaching or research position at a U.S. college or university. Contact NRL's program coordinator at sfrp@hro.nrl.navy.mil.

The **NRL/United States Naval Academy Cooperative Program for Scientific Interchange** allows faculty members of the U.S. Naval Academy to participate in NRL research. This collaboration benefits the Academy by providing the opportunity for USNA faculty members to work on research of a more practical or applied nature. In turn, NRL's research program is strengthened by the available scientific and engineering expertise of the USNA faculty. Contact NRL's program coordinator at usna@hro.nrl.navy.mil.

PROFESSIONAL APPOINTMENTS

Faculty Member Appointments use the special skills and abilities of faculty members for short periods to fill positions of a scientific, engineering, professional, or analytical nature at NRL.

Consultants and experts are employed because they are outstanding in their fields of specialization or because they possess ability of a rare nature and could not normally be employed as regular civil servants.

Intergovernmental Personnel Act Appointments temporarily assign personnel from state or local governments or educational institutions to the Federal Government (or vice versa) to improve public services rendered by all levels of government.

STUDENT PROGRAMS

The student programs are tailored to high school, undergraduate, and graduate students to provide employment opportunities and work experience in naval research.

The **Naval Research Enterprise Intern Program (NREIP)** is a ten-week summer research opportunity for undergraduate sophomores, juniors, and seniors, and graduate students. The Office of Naval Research (ONR) offers summer appointments at Navy laboratories to current college sophomores, juniors, seniors, and graduate students from participating schools. Application is online at www.asee.org/nreip through the American Society for Engineering Education. Electronic applications are sent for evaluation to the point of contact at the Navy laboratory identified by the applicant. Contact NRL's program coordinator at nreip@nrl.navy.mil.

The **National Defense Science and Engineering Graduate Fellowship Program** helps U.S. citizens obtain advanced training in disciplines of science and engineering critical to the U.S. Navy. The three-year program awards fellowships to recent outstanding graduates to support their study and research leading to doctoral degrees in specified disciplines such as electrical engineering, computer sciences, material sciences, applied physics, and ocean engineering. Award recipients are encouraged to continue their study and research in a Navy laboratory during the summer. Contact NRL's program coordinator at (202) 404-7450 or ndseg@hro.nrl.navy.mil.

The **Pathways Intern Program** (formerly STEP and SCEP) provides students enrolled in a wide variety of educational institutions, from high school to graduate level, with opportunities to work at NRL and explore Federal careers while still in school and while getting paid for the work performed. Students can work full-time or part-time on a temporary or non-temporary appointment. Students must be continuously enrolled on at least a half-time basis at a qualifying educational institution and be at least 16 years of age. The primary focus of our **Non-temporary** intern appointment is to attract students enrolled in undergraduate and graduate programs in engineering, computer science, or the physical sciences. Students on non-temporary appointments are eligible to remain on their appointment until graduation and may be non-competitively converted to a permanent appointment within 120 days after completion of degree requirements. Conversion is not guaranteed. Conversion is dependent on work performance, completion of at least 640 hours of work under the intern appointment before completion of degree requirements, and meeting the qualifications for the position. The **Temporary** intern appointment is initially a one year appointment. This program enables students to earn a salary while continuing their studies and offers them valuable work experience. NRL's Pathways Intern Program opportunities are announced on USAJOBS four times per year. Visit USAJOBS at https://www.usajobs.gov/ to create an account, search for jobs, set up an email notification alert of when positions of interest are posted (see "Saved Searches") and apply for our intern opportunities when posted. For additional information on NRL's Intern Program, visit http://hroffice.nrl.navy.mil/student/student_only.asp or contact (202) 767-8313.

The **Department of Defense Science and Engineering Apprenticeship Program (SEAP)** provides an opportunity for high school students who have completed at least grade 9, and are at least 15 years of age, to serve as junior research associates. Under the direction of a mentor, for eight weeks in the summer, students gain a better understanding of research, its challenges, and its opportunities through participation in scientific, engineering, and mathematics programs. Criteria for eligibility are based on science and mathematics courses completed and grades achieved; scientific motivation, curiosity, the capacity for sustained hard work; a desire for a technical career; teacher recommendations; and exceptional test scores. The NRL program is the largest in the Department of Defense. For detailed information visit https://seap.asee.org/, email seap@hro.nrl.navy.mil, or call (202) 767-8324.

The **Summer Research Program for Historically Black College or University (HBCU) or Minority Institution (MI)** is a ten-week summer internship program that provides opportunities for undergraduate and graduate students to participate in research under the guidance of a mentor at the Naval Research Laboratory. Preference is given to students planning careers in science, technology, engineering, and mathematics (STEM) disciplines. Applicants must be U.S. citizens or have permanent residency and be enrolled at an HBCU, MI, or Tribal College or University. Participating students receive a stipend. Information and application materials are available at: TWCIAS-NRL HBCU Information Page. Online applications can be found at http://nrl.e.twc.edu/.

VOLUNTEER OPPORTUNITIES

The **Student Volunteer Program** helps students gain valuable experience by allowing them to voluntarily perform educationally related work at NRL. It provides exposure to the work environment and also provides an opportunity for students to make realistic decisions regarding their future careers. Applications are accepted year-round. For additional information, visit http://hroffice.nrl.navy.mil/student/student_only.asp or contact (202) 767-8313.

NRL EMPLOYMENT OPPORTUNITIES

for Highly Innovative, Motivated, and Creative Professionals

NRL offers a wide variety of challenging S&T positions that involve skills from basic and applied research to equipment development. The nature of the research and development conducted at NRL requires professionals with experience. Typically there is a continuing need for electronics, mechanical, aerospace, and materials engineers, metallurgists, computer scientists, and oceanographers with bachelor's and/or advanced degrees and physical and computer scientists with Ph.D. degrees.

- **Biologists.** Biologists conduct research in areas that include biosensor development, tissue engineering, molecular biology, genetic engineering, proteomics, and environmental monitoring.

- **Chemists.** Chemists are recruited to work in the areas of combustion, polymer science, bioengineering and molecular engineering, surface science, materials synthesis, nanostructures, corrosion, fiber optics, electro-optics, microelectronics, electron device technology, and laser physics.

- **Electronics Engineers and Computer Scientists.** These employees may work in the areas of communications systems, electromagnetic scattering, electronics instrumentation, electronic warfare systems, radio frequency/microwave/millimeter-wave/infrared technology, radar systems, laser physics technology, radio-wave propagation, electron device technology, spacecraft design, artificial intelligence, information processing, signal processing, plasma physics, vacuum science, microelectronics, electro-optics, fiber optics, solid-state physics, software engineering, computer design/architecture, ocean acoustics, stress analysis, and expert systems.

- **Materials Scientists/Engineers.** These employees are recruited to work on materials, microstructure characterization, electronic ceramics, solid-state physics, fiber optics, electro-optics, microelectronics, fracture mechanics, vacuum science, laser physics and joining technology, and radio frequency/microwave/millimeter-wave/infrared technology.

- **Mechanical and Aerospace Engineers.** These employees may work in areas of spacecraft design, remote sensing, propulsion, experimental and computational fluid mechanics, experimental structural mechanics, solid mechanics, elastic/plastic fracture mechanics, materials, finite-element methods, nondestructive evaluation, characterization of fracture resistance of structural alloys, combustion, CAD/CAM, and multifunctional material response.

- **Oceanographers, Meteorologists, and Marine Geophysicists.** These employees work in the areas of ocean and atmospheric dynamics, air–sea interaction, upper-ocean dynamics, oceanographic bio-optical modeling, oceanic and atmospheric numerical modeling and prediction, data assimilation and data fusion, retrieval and application of remote sensing data, benthic processes, aerogeophysics, marine sedimentary processes, advanced mapping techniques, atmospheric physics, and remote sensing. Oceanographers and marine geophysicists are located in Washington, DC, and at the Stennis Space Center, Bay St. Louis, Mississippi. Meteorologists are located in Washington, DC, and Monterey, California.

- **Physicists.** Physics graduates may concentrate on such fields as materials, solid-state physics, fiber optics, electro-optics, microelectronics, vacuum science, plasma physics, fluid mechanics, signal processing, ocean acoustics, information processing, artificial intelligence, electron device technology, radio-wave propagation, laser physics, ultraviolet/X-ray/gamma-ray technology, electronic warfare, electromagnetic interaction, communications systems, radio frequency/microwave/millimeter-wave/infrared technology, computational physics, radio and high-energy astronomy, solar physics, and space physics.

For more information and current vacancy listings, visit http://www.nrl.navy.mil/careers.

General Information

NRL SCIENCE AS ART CONTEST

Space Systems Development Department Choice

Non-Uniformity

This image, created by a Silicon Imaging SI1920HD camera, illustrates an example of a process called “flat fielding” that flattens out inconsistent pixel behavior to correct for non-uniformities in a digital image. Your own digital camera, for instance, might produce an image with such non-uniformities because of lens glare or a dirty lens, and by using flat fielding, you could get rid of the non-uniformities and end up with a much better image. The image produced here by NRL researchers in the Space Systems Development Department is displayed via a Glasbey lookup table (LUT), a color table structured in a maximally discontinuous manner, i.e., adjacent color bins are chosen to be as distinct from one another as possible. The advantage of the Glasbey LUT is that it clearly depicts subtle changes that a standard gradient-based LUT might miss.

Conner Lowden and David Huber
Space Systems Development Department

TECHNICAL OUTPUT

The Navy continues to be a leader in initiating new developments and applying these advancements to military requirements. The primary method of informing the scientific and engineering community of the advances made at NRL is through the Laboratory's technical output — reports, articles in scientific journals, contributions to books, papers presented to scientific societies and topical conferences, patents, and inventions.

The figures for calendar year 2015 presented below represent the output of NRL facilities in Washington, D.C.; Bay St. Louis, Mississippi; and Monterey, California.

In addition to the output listed, NRL scientists made 1044 oral presentations during 2015.

Type of Contribution	Unclassified	Classified	Total
Articles in periodicals, chapters in books, and papers in published proceedings	1362*	0	1362*
NRL Formal Reports	9	1	10
NRL Memorandum Reports	53	1	54
Books	0	0	0
U.S. patents granted	133	0	133
Foreign patents granted	7		7
U.S. Trademark Registrations	7		7

*This is a provisional total based on information available to the Ruth H. Hooker Research Library on February 14, 2017. Additional publications carrying a 2015 calendar year publication date are anticipated. Total includes refereed and nonrefereed publications.

KEY PERSONNEL

Area Code (202) unless otherwise listed
Personnel Locator - 767-3200
DSN-297 or 754

Code	Office	Phone Number
	EXECUTIVE DIRECTORATE	
1000	Commanding Officer	767-3403
1000.1	Inspector General	404-3309
1001	Director of Research	767-3301
1001.1	Executive Assistant for the Director of Research	767-2445
1002	Executive Officer	767-3621
1004	Head, Technology Transfer Office	767-3083
1006	Head, Office of Program Administration and Policy Development	767-3091
1008	Office of Counsel	767-2244
1030	Strategic Communications Officer	404-3322
1100	Director, Institute for Nanoscience	767-3261
1200	Head, Command Support Division	404-1004
1220	Head, Information Assurance and Communications Security	767-0213
1400	Head, Military Support Division	767-2273
1600	Commander, Scientific Development Squadron One	301-342-3751
1700	Director, Laboratory for Autonomous Systems Research	767-2684
1800	Director, Human Resources Office	767-3421
1830	Deputy EEO Officer	767-5264
3005	Deputy for Small Business	767-6263
3540	Head, Safety Branch	767-2232
	BUSINESS OPERATIONS DIRECTORATE	
3000	Associate Director of Research	767-2371
3200	Head, Contracting Division	767-5227
3300	Head, Financial Management Division (Comptroller)	767-3405
3400	Head, Supply and Information Services Division	767-3446
3500	Director, Research and Development Services Division	404-4054
	SYSTEMS DIRECTORATE	
5000	Associate Director of Research	767-3425
5300	Superintendent, Radar Division	404-2700
5500	Superintendent, Information Technology Division/NRL Command Information Officer*	767-2903
5600	Superintendent, Optical Sciences Division	767-7375
5700	Superintendent, Tactical Electronic Warfare Division	767-6278
	MATERIALS SCIENCE AND COMPONENT TECHNOLOGY DIRECTORATE	
6000	Associate Director of Research	767-3566
6040	Director, Laboratories for Computational Physics and Fluid Dynamics	767-2402
6100	Superintendent, Chemistry Division	767-3026
6300	Superintendent, Materials Science and Technology Division	767-2926
6700	Superintendent, Plasma Physics Division	767-2723
6800	Superintendent, Electronics Science and Technology Division	767-3693
6900	Director, Center for Bio/Molecular Science and Engineering	404-6000
	OCEAN AND ATMOSPHERIC SCIENCE AND TECHNOLOGY DIRECTORATE	
7000	Associate Director of Research	404-8690
7100	Superintendent, Acoustics Division	767-3482
7200	Superintendent, Remote Sensing Division	767-3391
7300	Superintendent, Oceanography Division	228-688-4670
7400	Superintendent, Marine Geosciences Division	228-688-4650
7500	Superintendent, Marine Meteorology Division	831-656-4721
7600	Superintendent, Space Science Division	767-6343
	NAVAL CENTER FOR SPACE TECHNOLOGY	
8000	Director	767-6547
8100	Superintendent, Space Systems Development Department	767-0410
8200	Superintendent, Spacecraft Engineering Department	404-3727

*Additional Duty

CONTRIBUTIONS BY DIVISIONS, LABORATORIES, AND DEPARTMENTS

Radar Division

Information Technology Division

Optical Sciences Division

Tactical Electronic Warfare Division

Chemistry Division

Materials Science and Technology Division

Laboratory for Computational Physics and Fluid Dynamics

Plasma Physics Division

Electronics Science and Technology Division

Center for Bio/Molecular Science and Engineering

Acoustics Division

Remote Sensing Division

Oceanography Division

Marine Geosciences Division

Marine Meteorology Division

Space Science Division

Space Systems Development Department

Spacecraft Engineering Department

SUBJECT INDEX

AUTHOR INDEX

NAVAL RESEARCH LABORATORY

4555 Overlook Ave., SW • Washington, DC 20375-5320

LOCATION OF NRL IN THE CAPITAL AREA

Quick Reference Telephone Numbers

	NRL Washington	NRL-SSC	NRL-Monterey	NRL CBD	NRL VXS-1 Patuxent River
Hotline	(202) 767-6543	(202) 767-6543	(202) 767-6543	(202) 767-6543	(202) 767-6543
Personnel Locator	(202) 767-3200	(228) 688-3390	(831) 656-4763	(410) 257-4000	(301) 342-3751
DSN	297- or 754-	828	878	—	342
Direct-in-Dialing	767- or 404-	688	656	257	342
Strategic Comm.	(202) 767-2541	(228) 688-5328	(202) 767-2541	—	(202) 767-2541

Additional telephone numbers are listed on page 241.

General information on the research described in this *NRL Review* can be obtained from the Strategic Communications Office, Code 1030, (202) 767-2541. Information concerning Technology Transfer is available from the Technology Transfer Office, Code 1004, (202) 767-7230. Sources of information on the various educational programs at NRL are listed in the *NRL Review* chapter titled "Programs for Professional Development."

For additional information about NRL, the *NRL Fact Book* lists the organizations and key personnel for each division. It contains information about Laboratory funding, programs, and field sites. The Fact Book can be obtained from the Technical Information Services Branch, Code 3430, (202) 404-4963. The web-based NRL Major Facilities publication, which describes each NRL facility in detail, can be accessed at http://www.nrl.navy.mil/media/publications.

www.nrl.navy.mil

U.S. NAVAL RESEARCH LABORATORY
THE NAVY'S CORPORATE LABORATORY