NAVAL SCIENCE AND TECHNOLOGY

FUTURE FORCE™

VOL. 9, NO. 2, 2023

U.S. Naval Research Laboratory

Celebrating a Century of DISCOVERY and INNOVATION

U.S. NAVAL RESEARCH LABORATORY CENTENNIAL CELEBRATION 1923 - 2023

U.S. NAVAL RESEARCH LABORATORY

VOLUME 9
#02
2023

FUTURE FORCE

NAVAL SCIENCE AND TECHNOLOGY MAGAZINE

IN THIS ISSUE

COLUMNS

To submit an article or subscribe to *Future Force*, please visit our website or contact the managing editor.

Future Force Magazine
Office of Naval Research
875 N. Randolph Street, Suite 1425
Arlington, VA 22203-1995

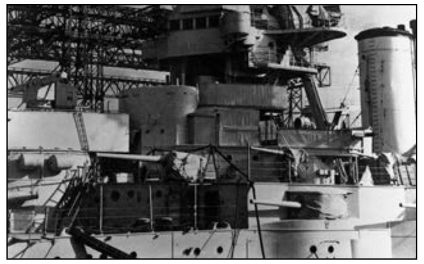
Email: futureforce@navy.mil
Phone: (703) 696-5031
Web: https://www.onr.navy.mil/en/Media-Center/futureforce
Facebook: http://www.facebook.com/navalfutureforce

BEYOND FUTURE FORCE

Interactive features are enabled with the digital copy of Future Force:
https://www.onr.navy.mil/en/Media-Center/futureforce

Mobile Download

NRL conducted the first US satellite program, developed America's first intelligence satellite, produced the first GPS satellite, and developed some of the most highly effective vehicles to have mapped the Sun and the Moon.



NRL's research and development in electromagnetic warfare continues a proud century-long tradition that remains essential to maintaining and extending the Navy's operations across the globe.

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

Front Cover: Designed by Daria Bodnaruk, NRL

SPEAKING OF S&T

▶▶ By Carlos Del Toro

Since its founding in 1923, the US Naval Research Laboratory (NRL) has had a powerful impact on our Navy, our Marine Corps, and indeed our nation. The technologies developed by NRL have supported our fleet and our force in both times of peace and conflict, from World War II to the present day.

Over its first 100 years, NRL has developed a wide-ranging portfolio of solutions to address a myriad of challenges in every domain we operate—at, above, and below the sea, as well as in space and cyberspace—demonstrating its workforce's mastery of several unique science and technology disciplines, as well as their ability to innovate with speed.

Alongside NRL, the Office of Naval Research (ONR) continues to be a major supporter of basic science and technology research across several disciplines, through significant financial investments, the technical expertise of its workforce, and partnerships across academia and industry.

Coupled with its investments in research, experimentation, and innovative capability development, ONR is investing in people—through grants, scholarships, and science, technology, engineering, and mathematics (STEM)-oriented programs.

ONR is also dedicated to developing our next generation of scientists, engineers, and researchers by providing research opportunities, internships and apprenticeships to high school students, undergraduates, and graduate students.

Reaching out across the entire nation, these students will no doubt be critical to the future development of technologies and capabilities that will prove to be critical to our fleet.

And as we move into this decisive decade, and the increased defense spending from our strategic partners, we are able to leverage and build from ONR's long-term and extensive science and technology network, where longstanding investments in the western Pacific, including Japan, South Korea, Pacific island nations, as well as our "Five-Eyes" and NATO allies, are crucial to developing and maintaining our strategic partnerships.

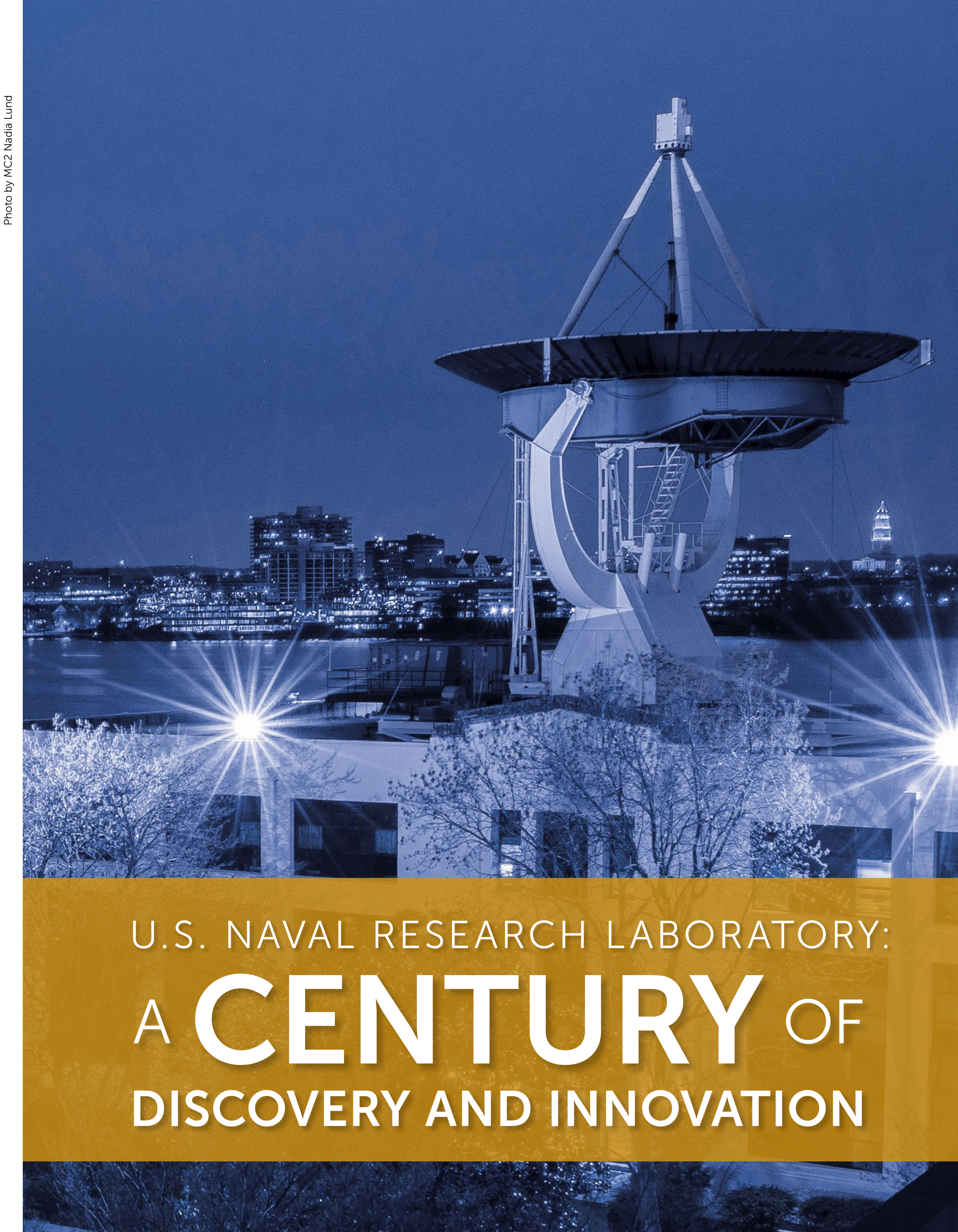
As our department continues to reimagine and refocus our innovation efforts, I encourage all of you—our nation's scientists, engineers, researchers, inventors, entrepreneurs, and problem-solvers—to join us.

We are indeed in an innovation race—and it is one we must win. Innovation must permeate every aspect of the Department of the Navy's approach to deliver the technologies and capabilities at a speed and scale necessary for our Navy and Marine Corps team to confront the challenges of today and the future—just as NRL has done for more than a century.

To the talented workforce of NRL, your efforts have contributed to peace, stability, and prosperity around the globe. Be proud of that and know that I am excited to support you in your future endeavors as you continue to advance our Navy, our Marine Corps, our nation, and indeed the world forward through your life-changing technology breakthroughs.

The Honorable Carlos Del Toro is the Secretary of the Navy.

Photo by MC2 Nadia Lund



U.S. NAVAL RESEARCH LABORATORY: A CENTURY OF DISCOVERY AND INNOVATION

A CENTURY OF DISCOVERY AND INNOVATION: AN INTERVIEW WITH DR. BRUCE G. DANLY

THE US NAVAL RESEARCH LABORATORY LIES AT THE FOCAL POINT WHERE RESEARCH, SCIENCE, AND WARFIGHTING INTERSECT THROUGH DIVERSITY OF THOUGHT, INCLUSION, INNOVATION, AND INTEGRATION. THE LABORATORY'S DIRECTOR OF RESEARCH TALKS ABOUT THE IMPORTANCE OF THE NAVY'S CORPORATE LABORATORY AND LEADING NAVAL RESEARCH INTO THE NEXT CENTURY.

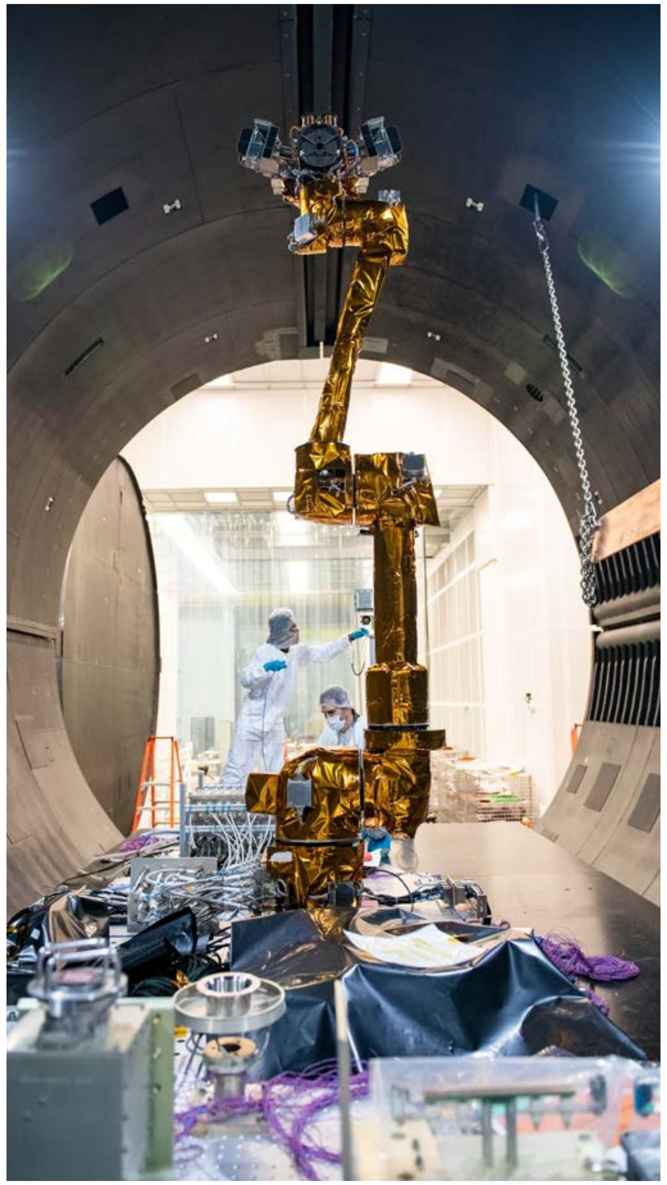


Photo by Sarah Peterson

For millennia, navies battled predominantly on the sea. Today, naval forces deploy, fight, and surveil on, in, above, and below the sea, on land, and in space.

In 1915, Thomas Edison's vision for the nation's strategic advantage looked far into the future: "The government should maintain a great research laboratory to develop guns, new explosives, and all the technique of military and naval progression without any vast expense."

Since 1923, the US Naval Research Laboratory (NRL) has played a critical role in a myriad of basic to applied research programs and technical efforts across the Department of Defense, government, industry, and academia. NRL's enduring mission is to provide the necessary tools and technologies to deter war and protect the security of our nation across all domains—air, cyber, electromagnetic, ground, information, sea, and space.

Today, NRL is the Department of the Navy's lead laboratory in naval-specific space systems research, as well as in fire, tactical electronic warfare, microelectronics, and artificial intelligence research. The laboratory focuses 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.

The interdisciplinary and wide-ranging nature of NRL's work keeps this "great research laboratory" at the forefront of discovery and innovation to solve naval challenges—to the benefit of the nation as a whole.

Dr. Bruce Danly recently discussed the role NRL plays within the Naval Research and Development Establishment (NR&DE) in supporting the Department of the Navy's efforts to retain and grow its technological advantage and maritime superiority.

How has Thomas Edison's founding vision advanced military operations and naval research since 1923?

The long list of innovations and contributions to the Navy and Marines Corps over the past century by the Naval Research Laboratory are a testament to the wisdom of Edison and Secretary [of the Navy Josephus] Daniels to establish the laboratory in 1923. As a part of our centennial celebration, the laboratory has published a sampling of the hundreds of innovations NRL has delivered to the Navy over the past century.[1] This listing represents but a hundred of the many contributions deemed appropriate for public release in honor of our centennial. Many more contributions, not yet public, add to this impressive list of accomplishments attesting to the vision of Edison and Daniels.

How has NRL empowered strategic military operations for 100 years?

NRL has empowered strategic military operations in the past century through two main approaches. One, by developing advanced technologies designed to give US naval forces the edge in any future conflict, and two, by serving as technical "honest broker" advisors to Navy leadership on the capabilities and limitations of US military systems and the systems of potential adversaries.

What is the role of basic scientific research for the Navy and Marine Corps?

The performance of use-inspired basic scientific research is a key part of NRL's research portfolio. The laboratory performs basic research that is determined to be of likely future value to the Department of the Navy; this naval use-inspired or "Pasteur's Quadrant" basic research[2] forms the foundation for follow-on applied research and advanced development that otherwise may not have received the same attention, or any attention, in the commercial sector. Many advanced technologies that benefitted the department for military application acquired their start as basic research at the laboratory.

How important is it for the Department of Navy to dedicate resources to infrastructure and talent to address today's warfighter needs?

The main laboratory site, chosen over a century ago to be at the Bellevue Magazine site in the District of Columbia as a compromise over two other more prominent sites in Maryland and New Jersey, is showing its age. The average age of the buildings at this NRL-DC site is now 67 years old, with some buildings dating from before the lab's founding. The pace of recapitalization of these buildings has fallen far behind what is necessary, even by DoD standards, for building recapitalization. Military construction funding for building replacements has been very limited, in part due to Department of the Navy perceptions of higher priority shore infrastructure needs. The state of some of our buildings is now impacting workforce retention, notwithstanding the fact that NRL continues to employ top scientists and engineers and that our buildings house state-of-the-art scientific research equipment. We clearly need a focused effort by the Department of the Navy, with assistance from Congress, to recapitalize the laboratory's infrastructure.

How do NRL scientists and engineers fit into the Naval Research Enterprise?

The NRL scientists and engineers form the backbone of the in-house basic and applied research innovation ecosystem for the department. Together with all the key support workforce, including, administration, financial, legal, security, and safety, to name but a few, the NRL team forms a critical science and technology component of the Naval Research Enterprise (NRE). The broader NRE includes the Office of Naval Research (ONR), ONR Global, PMR-51, NavalX, and NRL. The laboratory works closely with these components of the naval science and technology community to maximize the development and rapid insertion of technologies to the fleet.

How are we going to deliver competitive advantage to the next generation of Sailors and Marines?

We are delivering competitive advantage to the next generation of Sailors and Marines through all the roles of a corporate research laboratory. NRL provides emerging technologies, either directly, or through naval warfare center and industrial partners, to these warfighters on the front lines. In some cases, NRL even provides rapid response technology when called upon through urgent operational needs statements. NRL also provides technical advice to influence the development of tactics, techniques, and procedures (TTPs) by the department leadership and the naval warfare development commands; these TTPs are then used in the operational training of our Sailors and Marines.

What specific research areas are required for the United States to maintain maritime superiority?

There are many specific research areas needed to maintain maritime superiority. These include research areas called out in the Office of the Under Secretary of Defense for Research and Engineering critical technology area lists, in the Naval Science and Technology Strategy [in final draft as of this writing], and in numerous other niche scientific disciplines. Widely appreciated research areas include synthetic biology, quantum information sciences, advanced materials and additive manufacturing, space sciences, and sensor, cyber, and information sciences. Many of these areas have commercial non-defense applications that help in driving the innovation. Areas without significant commercial interest that are very important to the department include electromagnetic warfare and undersea warfare-related technologies. The laboratory conducts research in all these areas.

How is new knowledge the real source of future competitive advantage?

New knowledge is the real source of future competitive advantage, whether developed in US universities, the private sector, or at a government laboratory like NRL. The US competitive advantage fundamentally comes from the strength of our economy and our national innovation ecosystem. NRL contributes significantly to this, through our patent portfolio and licensing. A study[3] on national economic impacts from DoD patent license agreements determined that NRL has accounted for a total economy-wide impact of $2.3 billion (39 percent of all Navy impact) and a private sector employment of 9,261 (41 percent of Navy) jobs attributable to NRL's licensing agreements from 2000-2021.

In addition to NRL's contributions to bolster our national economic activity, NRL remains focused on providing the US military competitive advantage by generating new warfare-related technologies. The responsibility to lead in the direct development of this type of military competitive advantage is the principal purposes of NRL, as originally envisioned by Thomas Edison and Secretary of the Navy Josephus Daniels. In international and natural conflicts since 1923, naval warfighters have benefitted from NRL-generated technology and will do so in the decades to come.

References

[1] *https://www.nrl.navy.mil/Portals/38/NRL%20100%20 Contributions_508_reduced_1.pdf*

[2] *Donald E. Stokes, Pasteur's Quadrant: Basic Science and Technological Innovation (Washington, DC: Brookings Institution Press, 1997).*

[3] *National Economic Impacts from Department of Defense License Agreements with US Industry, TechLink, https://techlinkcenter.org/economic-impact-reports/national-economic-impacts-of-dod-technology-license-agreements-with-u-s-industry-2000-2021.*

About the subject and author:

Dr. Danly is the director of research at the US Naval Research Laboratory.

Nicholas Pasquini is a writer with US Naval Research Laboratory corporate communications.

Photo by Jim Meiklejohn

NRL: 100 YEARS STRONG

THE BRAINCHILD OF THE NATION'S MOST FAMOUS INVENTOR DURING THE FIRST GLOBAL WAR OF THE 20TH CENTURY, THE US NAVAL RESEARCH LABORATORY HAS NOW SPENT A CENTURY SUPPORTING THE NAVY AND MARINE CORPS, EXPLORING OUR PLANET'S INNER SPACES AS WELL AS OUTER SPACE, AND DISCOVERING AND DEVELOPING THE SCIENCE AND TECHNOLOGY THAT HELP MAKE TODAY'S WORLD POSSIBLE.

Commissioned on 2 July 1923 as the Naval Experimental and Research Laboratory (later shortened several years later to the Naval Research Laboratory), NRL has changed the way the military fights, improved its capabilities, prevented technological surprise, transferred vital technology to industry, and tilted the world's balance of power on at least three occasions: the first US radar, the world's first intelligence satellite, and the first operational satellite of the Global Positioning System (GPS).

A Vision Realized

In 1873, the federal government purchased 90 acres of Bellevue in southwest Washington, DC, and added this land to the adjacent Naval Gun Factory at the Washington Navy Yard. This land was known as the Bellevue Annex to the Naval Gun Factory until 1923, when the federal government opened the US Naval Research Laboratory on the site. The laboratory remains on this tract of land to this day.

In a 1915 New York Times article, Thomas Edison suggested that the government should maintain a "great research laboratory." With this interview and with the progression of World War I, the idea of a central research facility for the Navy began to take shape.

Secretary of the Navy Josephus Daniels seized the opportunity created by Edison's public comments to enlist Edison's support. Edison agreed, serving 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 eventual recommendation was "for the: establishment of a research and experimental laboratory, whose investment for grounds, buildings, and equipment should total approximately $5,000,000, and which should be located on tidewater of sufficient depth to permit dreadnought [class battleships] to come to the dock . . . near, but not in, a large city, so that labor and supplies might be easily obtained."

Assistant Secretary of the Navy Theodore Roosevelt Jr. delivers the principal address at NRL's commissioning ceremony with Navy and civilian dignitaries on 2 July 1923. NRL photo

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. On 6 December 1920, Daniels broke ground for NRL's Building 1.

Radio Silence

In September 1922, nearly eight months prior to the grand opening of the newly created laboratory, two Navy radio engineers Albert Hoyt Taylor and Leo Clifford Young stationed at the Naval Aircraft Radio Laboratory at Anacostia, just north of Bellevue, began to seek new frequencies for radio communication. Building a high-frequency transmitter and portable receiver, the two set out to "field-test" their device.

As Taylor and Young were testing their new equipment across the half-mile stretch of the open Potomac, the steamer Dorchester was cruising up the Potomac from Alexandria. As the vessel steamed toward the Anacostia River, the researchers took note to the discernable fluctuations and peaks they were observing on their equipment. After somewhat tweaking the efficiency of the signal, the scientists were soon able to more effectively identify approaching vessels along the river, some as far off as three miles. It was soon after this discovery the team truly believed they could further develop their device for practical military use in modernizing the efficiency of detecting ships.

Unfortunately, no part of the Navy seemed interested at the time, and Taylor and Young, in lieu of other demanding priorities, shelved the project before being moved slightly down river to the newly commissioned Bellevue lab several months later.

At NRL, Taylor became chief radio scientists of the laboratory's Radio Division and Young his top assistant. During the greater portion of the 1920s, the division was tasked with advancing high-frequency radio technology for service to the Navy fleet.

1923 and Beyond

After opening its doors, 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 the United States.

Nearly a decade after Taylor and Young's breakthrough in detecting distant moving objects via radio, a patent for "System for Detecting Objects by Radio," was approved in November 1934. Later referred to as radar (for "radio detection and ranging"), the technology contributed to major naval victories in battles at the Coral Sea, Midway, and Guadalcanal during World War II.

During the war, scientific activities necessarily were concentrated almost entirely on applied research. New electronics equipment in radio, radar, and sonar advanced quickly. 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 uranium-235 isotope needed for one of the first atomic bombs.

During the years since World War II, the laboratory has conducted basic and applied research pertaining to the Navy's environments of earth, sea, sky, space, and

The first US radar tested for shipboard service, similar to this one shown in 1937, was installed aboard the destroyer USS *Leary* (DD 158) before a fully operational system was later put on the battleship USS *New York* (BB 34). NRL photo

cyberspace. Investigations have ranged widely, from monitoring the sun's behavior to analyzing marine atmospheric conditions and measuring parameters of the deep oceans.

Laboratory researchers 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. 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 to stare down massive jamming tactics.

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, biotechnology, 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) and development of the world's first intelligence satellite (GRAB-I), to inventing and developing the first satellite prototypes of the modern-day GPS.

Office of Naval Research

Because of the major scientific accomplishments of the war years, the United States emerged into the postwar era determined to consolidate its 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 the Office of Naval Research (ONR) as a liaison with and supporter of scientific research, it was also encouraging NRL to broaden its scope. Placement of NRL within the Navy secretariat allowed it to pursue long-range high-risk projects and serve the Navy in the broadest sense.

Commissioned on 1 August 1946, 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 the war 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 NRL Robotic Servicing of Geosynchronous Satellites (RSGS) integration and test team analyzes data collected from contact dynamic testing on a robotic test bed in 2022. Contact dynamic testing allows the team to characterize how the payload will behave when servicing client spacecraft. Photo by Sarah Peterson, NRL

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.

Leading Naval Research into the 21st Century

Today, NRL leads advances for the Navy in naval-specific space systems development and support, as well as in fire research, tactical electronic warfare, microelectronic devices, and artificial intelligence. The laboratory now focuses 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 strive 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, to include innovations in wireless transfer of solar energy; hypersonic technologies and quantum information science.

NRL also moves technology rapidly from concept to operational use when high-priority, short-term needs arise. Some past examples are pathogen detection, lightweight body armor, contaminant transport modeling, and communications interoperability.

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.

CONTROLLING THE BATTLESPACE

THE NAVAL RESEARCH LABORATORY HAS A LONG HISTORY OF DEVELOPING TECHNOLOGY THAT PROVIDES SITUATIONAL AWARENESS IN ANY ENVIRONMENT, FROM THE SEAFLOOR TO OUTER SPACE.

A century of work by the Naval Research Laboratory (NRL) has enabled American, partner, and allied military and civilian operations to go beyond modern limitations. NRL's ongoing research has unlocked the world's best forecasting, sensing, and wayfinding technologies. These continuing breakthroughs profoundly shape US military strategy as well as civilian life.

Today, NRL technologies are used by all branches of the Department of Defense (DoD), the Department of Energy, the National Oceanic and Atmospheric Administration (NOAA), NASA, and thousands of private companies in operations worldwide.

Windspeed Measurement Using Microwave Imaging

In 1966, NRL pioneered the use of passive microwave sensing to measure ocean-surface roughness and to derive surface wind speed. Operational use of this technology began in 1988 and evolved in 2003 to include polarimetry metrics to sense wind direction.

Due in large part to NRL's efforts, satellite passive microwave sensing is now the primary source of ocean-surface wind speed data and weather prediction models used by both civilian and military forecasters. Building on this foundation of essential invention, NRL is currently developing a next-generation weather satellite system in collaboration with the DoD.

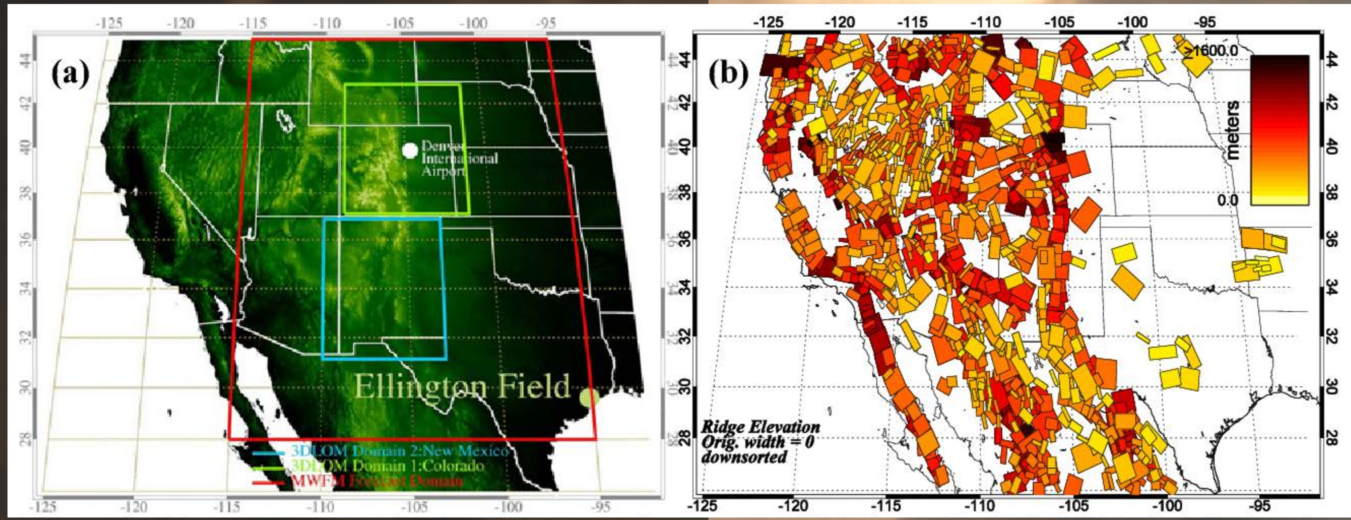
Global Weather Prediction

Since 1976, NRL research has provided atmospheric and oceanographic prediction for military and civilian applications, including ship and aircraft navigation, weapons and sensing platforms efficacy, and "near space" (10-100 kilometers) environmental information for the development and testing of emerging Navy assets.

Today, NRL's weather prediction systems (Naval Operational Global Atmospheric Prediction System [NOGAPS]/Navy Global Environmental Model [NAVGEM]) are the DoD's unified, global, weather-analysis-and-forecast systems that provide operational weather prediction around the world. NAVGEM is the world's first prototype of a global, numerical, weather-prediction system extending from the ground to the edge of space and is used by all branches of the armed services, NOAA, and the Department of Energy.

Fiber-Optic Interferometric Acoustic Sensors

NRL demonstrated and patented the first fiber-optic interferometric acoustic sensor in 1977. Since then, fiber-optic sensors have been used in applications that include electric, magnetic, temperature, materials stress, and countless others.



Mountain waves—gusts of wind that rise and fall alongside mountains—are among the most hazardous conditions that aircraft encounter. NRL developed a model to predict them in the 1990s. NRL graphic

NRL's development of a fiber-optic sensor system led to the now-ubiquitous presence of fiber-optic sensor devices. These devices have transformed interferometric sensing and enabled measurements in acoustic, magnetic, electric, thermal, vibration, and flow applications, which are commonly seen in air traffic control, medical care, construction safety, and seismology.

Currently, the Lightweight Wide Aperture Array, an NRL-developed, large-channel-count fiber-optic acoustic-array, first deployed in 2004, conveys depth by measuring oceanic pressure and is built into the hulls of Virginia (SSN-774) class nuclear-powered attack submarines.

Optical Fiber Gyroscopes

NRL was the first to demonstrate long-term, inertial-quality performance in a fiber-optic gyroscope for use in navigational technology. This achievement was a pivotal milestone in the device's development into a practical and precise navigation instrument, sparking widespread industrial development for its use in sea, air, and space technologies.

The fiber-optic gyroscope revolutionized rotation-sensing technology with its higher reliability, longer lifetime, and weight, size, and cost reduction compared to the spinning-mass gyroscopes commonly used before 1983. The optical fiber gyroscope is now in production across the globe and can be seen in military and civilian applications ranging from use on automobiles as well as military platforms.

El Niño

In 1994, NRL research demonstrated for the first time that oceanic effects of major atmospheric events can be extremely long-lived.

US Air Force photo by Technical Sgt. Chris Hibben

NRL provided evidence from modeling and observations that planetary-scale oceanic waves crossed the North Pacific Ocean during the 1982-1983 El Niño season and, a decade later, caused a northward rerouting of the Kuroshio Extension. The Kuroshio Extension normally transfers large amounts of heat from the southern coast of Japan eastward, into the mid-latitude Pacific. NRL research, however, demonstrated that high latitudes of the Pacific also experienced significant sea-surface temperature increases with the same amplitude and spatial extent as those seen in the tropics during important El Niño events. Data suggested that these changes may have influenced weather patterns over North America during the decade following the 1982-1983 El Niño.

The scientific importance of this discovery was noted in Nature, and was recognized as one of the year's top 75 science stories by Discovery magazine in 1994.

Mesoscale Prediction Systems

NRL's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS), first developed in the early 2000s, continues to provide high-resolution predictions of the environment that enhance tactical applications and worldwide operations.

The unique atmospheric component technology in COAMPS enables more accurate forecasts over areas that exhibit steep topographic features and strong convection. The system predicts tropical cyclone track and structure, distribution of aerosols, and explicitly predicts water and ice clouds, as well as rain and snow. This world-class and exclusive capability enables new and extensive research on phenomena such as tropical cyclones, explosive cyclogenesis, and electromagnetic and acoustic propagation.

Environmental prediction products from COAMPS are distributed to DoD commands around the world to support mission planning, ship and aircraft operations, and hazardous weather avoidance. The system's data are also used by academic institutions and government organizations.

Mountain Wave Forecast

Mountain waves are among the most hazardous conditions that aircraft encounter. They are the result of air rising up the windward side of a mountain and then, under certain atmospheric conditions, descending on the leeward side. This results in the formation of a series of standing waves downwind from the mountain that may extend over considerable areas and form a potential flight hazard.

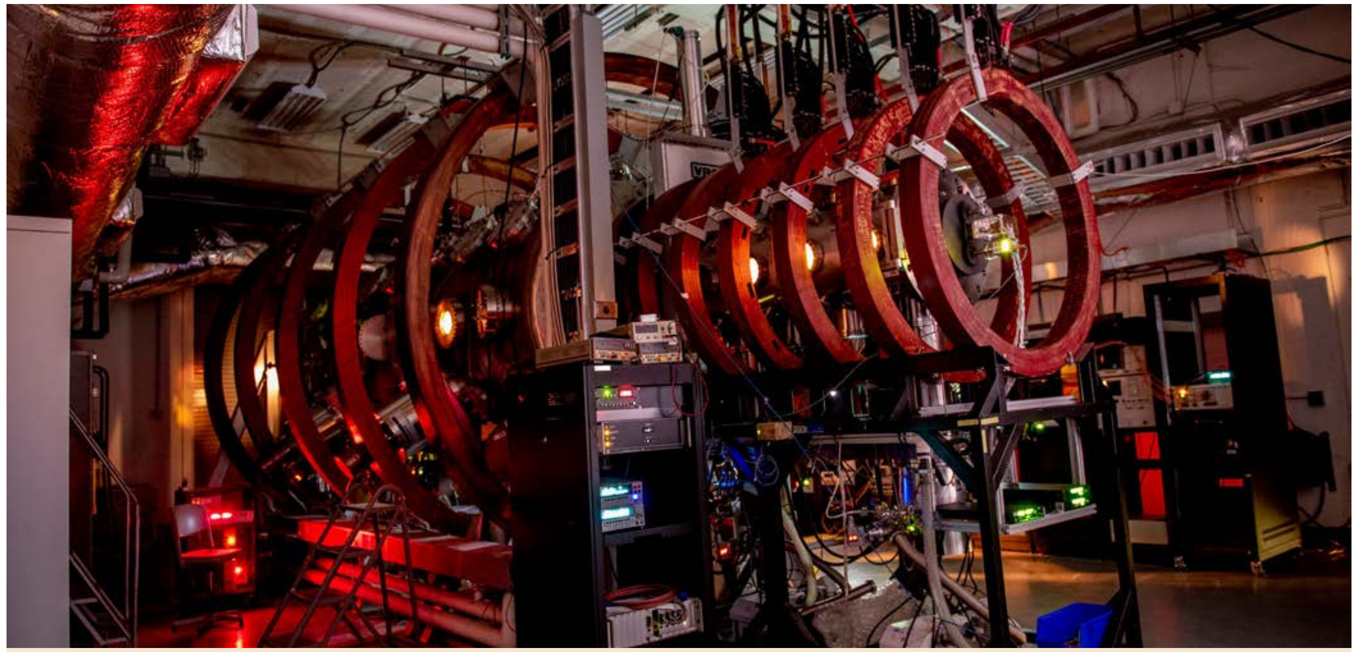
In response to these challenges, in the 1990s NRL developed the Mountain Wave Forecast Model (MWFM), the only meteorological model capable of globally forecasting mountain wave activity and wave-induced turbulence in the Earth's atmosphere, from near the surface to beyond 100,000 feet. MWFM is also a valuable tool for fundamental atmospheric research.

The MWFM, adopted for operational use by the Air Force, is a significant tool in identifying and forecasting middle- and upper-atmosphere turbulence and reducing risks to in-flight military and civilian aircraft. The model was used during operations Southern Watch, Enduring Freedom, and Iraqi Freedom, as well as in other operations around the world.

WindSat

Launched in 2003, NRL's WindSat was the first satellite-based polarimetric microwave radiometer. WindSat's mission was to test and evaluate the viability of using passive polarimetric radiometry to retrieve the ocean surface wind vector (wind speed and direction) from space. WindSat also measures sea surface temperature, total precipitable water, integrated cloud liquid water, rain rate over the ocean, soil moisture, and sea ice. Operating over multiple frequencies and polarizations, the radiometer measures microwave energy emitted from the ocean surface. NRL developed ground processing algorithms to convert these raw data into useful environmental intelligence products. WindSat provided valuable operational data from 2005 through the end of its mission in 2020.

WindSat, launched in 2003, was built to retrieve the ocean wind speed and direction from space. NOAA photo



Opened in 1990, the Space Physics Simulation Chamber Laboratory was developed to conduct investigations into the dynamic behavior of plasmas scaled to near-Earth space conditions. NRL photo

In more than 17 years in orbit, WindSat far exceeded its original mission objectives. WindSat data were ingested into the Navy Global Environmental Model, as well as civilian numerical weather models of NOAA and the UK Meteorology Office. The Joint Typhoon Warning Center and the National Hurricane Center used WindSat data to improve monitoring and forecasting of tropical cyclones. NRL's provision of more accurate forecasting saves the Navy millions of dollars annually in storm preparations and avoidance by the fleet.

Modern Space Plasma Physics

After the nuclear test ban treaty was signed in 1963, atmospheric experiments could no longer be performed to test high-altitude nuclear detonation effects on the upper atmosphere and near-Earth space plasma environments. The need to develop computer models to simulate, understand, and predict the consequences of these types of events led to the establishment of NRL's Plasma Physics Division, supported by the Defense Nuclear Agency.

NRL's initial efforts laid the foundation for the United States to continue to assess nuclear weapons effects. These efforts led to modern space plasma research through models such as the Lyons-Fedder-Mobary global magnetospheric model for space weather, and the 2D and 3D SAMI global ionospheric models. NRL's Space Physics Simulation Chamber, a state-of-the-art experimental facility, was constructed to test and validate theoretical discoveries of plasma microprocesses vital for ionosphere-magnetosphere coupling and to complement ground and space-based experimentation.

Together, NRL's theoretical and experimental results help enable the exploitation of plasma physics for space domain awareness and control for the DoD.

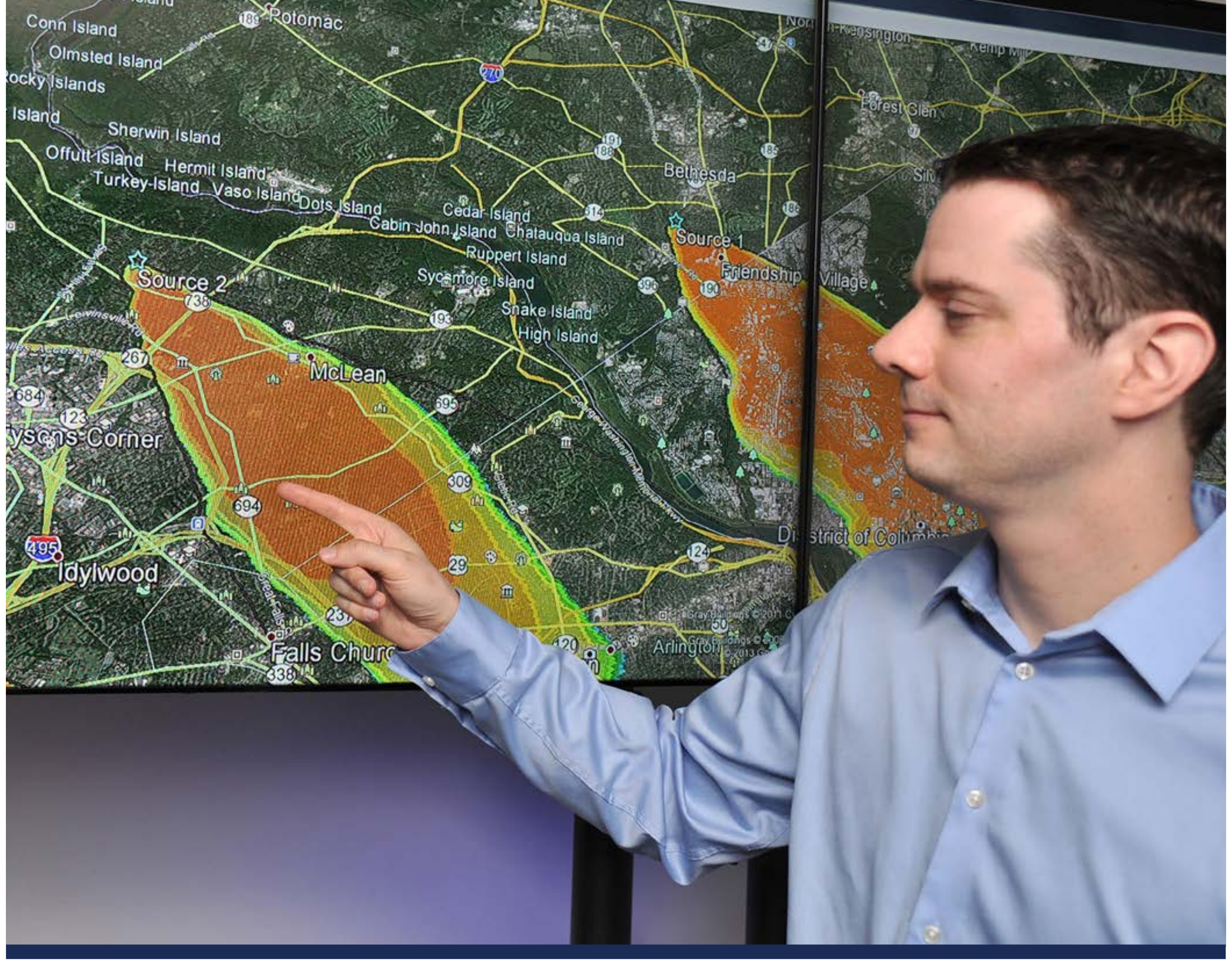
Rapid Radiation Belt Remediation System

Space is the ultimate high ground for 21st century warfare. Naval operations are critically dependent on space-based sensors. High-altitude nuclear detonations could cripple naval operations and space assets as well as severely harm the national economy.

Therefore, NRL has developed a Rapid Radiation Belt Remediation concept to rapidly precipitate the "high-energy" electrons that are generated as detonation byproducts within minutes of deployment and reduce or eliminate their lethality.

The key physics of the concept have been validated in laboratory experiments. The planned Space Measurement of a Rocket Released Turbulence (SMART) mission will test it in the actual theater of operation. NRL's development of these countermeasures will protect critical Navy/DoD space-based sensors from severe radiation damage and assure seamless information flow to warfighters.

Photo by Jamie Hartman



WARFIGHTER PERFORMANCE AND PROTECTION

NRL HAS LONG SOUGHT STRATEGIC ADVANTAGES THAT SAVE LIVES. THIS INCLUDES IMPROVED MATERIALS OF ALL KINDS, NEW SENSOR METHODS, NEW MEDICINES AND ARMORS, AND MANY MORE DEVELOPMENTS ON THE HORIZON.

NRL is committed to protecting warfighters and enhancing their performance in every arena. Over the past century, NRL has made significant contributions to this mission and will continue to work tirelessly towards ground-breaking achievements in the future.

Improved Aircraft Canopy and Window Materials

In the 1950s, NRL researchers tackled the problem of blow-out failures of combat aircraft canopies that resulted from the canopy material's inability to halt the propagation of cracks after impacts.

Shattering hundreds of canopies and painstakingly reassembling them, NRL researchers devised a new technique of acrylic "hot stretching" that significantly improved the toughness of the material. The new material was stronger, lighter, and more long-lasting than anything before. It is now employed on canopies and windows for both military and civilian aircraft, thereby reducing the likelihood of a canopy blow-out fatal accident.

Radiation Protection

NRL recognized the need for accurate and convenient dosimetry soon after the discovery of ionizing radiation, and developed several dosimeters through the 1950s and 1960s to address rising warfighter protection needs. These dosimeters were faster, cheaper, and more effective than any method available at the time.

The Navy and Air Force purchased several million NRL dosimeters for personnel monitoring in case of nuclear attack, providing warfighters with an effective, convenient, and economical diagnostic tool for radiation exposure. These dosimeters also served medical uses in the private sector in areas such as clinical radiology and cancer treatment.

In the 21st century, NRL also developed the Mobile Imaging and Spectroscopic Threat Identification (MISTI) system, as well as the second-generation SuperMISTI. SuperMISTI detects and identifies gamma ray sources more accurately and from greater distances than any system before, providing additional layers of radiation protection to warfighters as well as additional methods and tools for government researchers.

Nuclear Reactor Safety

All military and civilian nuclear reactors that feature a steel pressure shell are based on construction principles developed by NRL.

Throughout the 1960s, NRL researchers conducted many high-profile experiments to determine the safety of various reactor components, shells, and materials. These experiments were closely watched by the international community, the Atomic Energy Commission, and the US Army.

NRL's work ultimately resulted in the development of new radiation-resistant steels, which are used in new reactors throughout the world, and in the assurance of containment safety in older reactors, as well as rules of reactor operation that are still viewed as the landmark guide for specialists worldwide.

Marine Surface Monolayers

Since the early 1960s, NRL has performed extensive research on surface-active substances at critical interfaces in the marine environment. This research led to major breakthroughs in oil spill control, seamarkers, and mosquito control.

NRL researchers devised a new technique of acrylic "hot stretching" that significantly improved the toughness of aircraft canopy material, such as on this Convair F-102 Delta Dagger. The new material was stronger, lighter, and more long-lasting than anything before. NRL photo

NRL was the first to discover that certain surface films applied around oil spills could compress the oil into a much smaller area and maintain the oil in a thick layer. These films greatly enhance the efficiency of oil recovery operations and have been used by both the Navy and the private sector to control spills around the world.

NRL also pioneered the use of monolayers for seamarker purposes. Beyond the standard green dye, NRL's one-molecule-thick compound spreads more quickly and leaves a much larger mark than other substances. This compound is easily detectable both visually and by radar, enhancing warfighter performance and air-sea rescue operations.

NRL also developed a thin surface film that prevents mosquitos in the pupal and larval stages from attaching to the water's surface where they breathe and feed. This causes them to drown, thus killing by physical, rather than toxic, means. No pesticide is required nor is a petroleum-based solvent needed to deliver the compound. The method has proven effective against mosquito genera, which are carriers of tropical diseases, including malaria. The commercially manufactured compound has been used in mosquito control districts across the United States.

During the 1950s and 1960s, NRL developed several dosimeters to address rising radiological protection needs. These dosimeters were faster, cheaper, and more effective than any method available at the time. NRL photo

Purple-K-Powder

NRL's development of the potassium bicarbonate dry chemical extinguishing agent now known as Purple-K-Powder, more commonly known as PKP, represented a major advancement as an agent for combating and protecting against flammable liquid fire protection.

Working with other investigators, NRL conducted fire tests with many powdered substances, coming to the conclusion that the substitution of the potassium ion for sodium extended the flame-quenching efficiencies of the chemical powders by a factor of two, meaning PKP extinguished a fuel fire in half the time, or extinguished twice as much fire as before, in addition to providing much greater protection against re-flash.

PKP became used throughout the Navy and in municipal and industrial fire protection operations, and thereafter throughout the world.

Optical Immunoassays and Sensors

Beginning in the 1990s, NRL developed a collection of portable biosensors intended to be sensitive, simple to use, and requiring only minimal sample processing.

NRL's Fiber Optic Biosensor and the Continuous Flow Sensor are used for monitoring the presence of explosives in groundwater and soil. These systems, as well as the Array-Based Biosensor, are also used to measure toxins in river water and clinical samples. They have applications in drug detection and food contaminant detection.

NRL's advanced biosensors are now used throughout the public and private sectors, providing results comparable to the most sophisticated laboratory techniques. They continue to provide automated, sensitive detection of biological threats, contaminants, drugs, and explosives in many different scenarios.

CT-Analyst

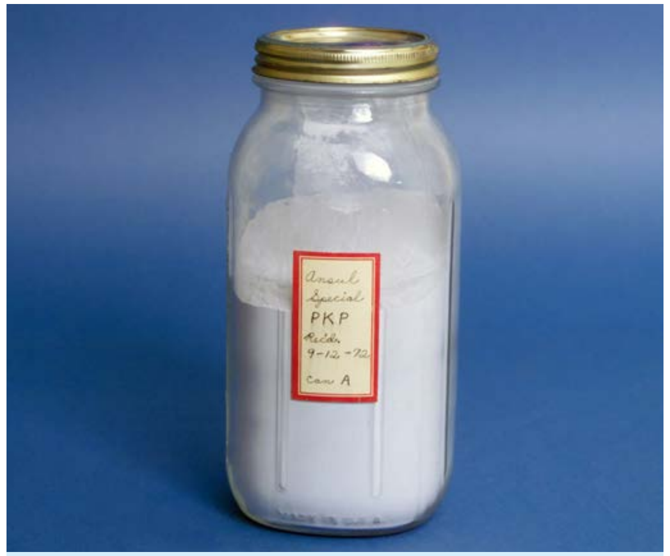
NRL's Contaminant Transport (CT) Analyst system is the first operational instantaneous emergency assessment system for airborne contaminants and weapons of mass destruction threats in cities.

CT-Analyst is based on NRL's work in fluid dynamics and atmospheric research and creates detailed models of airflow over cities in the event of a dangerous threat. CT-Analyst is more accurate and much faster than comparable systems, capable of providing a situation assessment in less than a second, while other systems can take hours.

CT-Analyst is used by warfighters and emergency managers around the world. It has been a key line of defense for presidential inaugurations, Super Bowls, award shows, State of the Union events, and many more significant events.

Silent Guardian

Silent Guardian is NRL's name for its Re-sequencing Pathogen Microarray (RPM) technology. First developed to ensure safety at the 2005 presidential inauguration, RPM moved from the research phase to full operational capability in less than six weeks. The system can identify up to 100 different pathogens in a single test using genetic sequencing and bioinformatics algorithms.



In 1959, a series of investigations by NRL in the area of chemical flame extinction gave birth to the discovery of a new dry chemical agent called potassium bicarbonate powder—or "Purple-K-powder"—used for chemical liquid fire protection. NRL photo

RPM technology was transferred to the private sector in 2007, earning NRL a Federal Technology Transition award. The commercial RPM was a key line of defense during the 2009 H1N1 influenza pandemic and is still in widespread use today.

Next-Gen Body Armor

NRL's QuadGard body armor is the result of a rapid-response program to protect warfighters from the severe limb injuries caused by improvised explosive devices.

With NRL's work beginning in 2004, QuadGard transitioned from concept to combat use in only 17 months and was immediately fielded by Marines in Iraq, followed by other Navy applications. Weighing only 10 pounds, the body armor incorporated the latest ballistic materials into innovative designs developed through exhaustive and ground-breaking research.

QuadGard protected warfighters operating gun turrets on road convoys and construction equipment in mined areas.

Transparent Armor

Transparent armor, also known as ballistic glass, is essential to warfighter protection. Each year, the Department of Defense spends tens of millions of dollars and thousands of hours on its upkeep and replacement on tactical vehicles.

From 2011 to 2013, NRL pioneered a new range of repair methods that could be performed at a fraction of the cost and time previously required. This research changed transparent armor from a short-lived and costly consumable to a repairable item with a greatly improved operational lifespan.

Estimated to save the Marine Corps $105 million over a five-year period, in 2018, NRL was recognized as part of a team that received the Navy "Innovation Excellence Acquisition Team of the Year Award" for these repair solutions.

Tissue Engineering

Advanced medical help is often unavailable to expeditionary and isolated warfighters, and even minor wounds can become infected and escalate rapidly to a life-threatening situation. NRL's improved wound monitoring and treatment will help provide wounded warfighters medical attention to ensure their survival and resilience.

This is achieved through Transferrable Active Chemical Structures (TACS), which delivers information to cells through electronic or biochemical means. Developed by NRL's Chemistry Division, this simple and inexpensive technology may eventually be used to design advanced wound dressings and monitoring devices.

Spinel, developed at NRL during the 2000s, is a form of transparent armor made from magnesium aluminate. NRL photo

Ultraviolet Disinfection Techniques

With the onset of the COVID-19 pandemic, NRL established a dedicated ultraviolet (UV) characterization lab in just five days to ensure safe introduction and effective operation of UV disinfection techniques across the fleet.

UV light disinfects materiel going onto a ship, in common use areas on a ship, and is a key element of general room disinfection on ships and shore facilities.

Studying energy density, UV spectrum, efficacy, and reliability, NRL was at the forefront of the Navy's research guiding acquisition of UV light systems that protected service members from COVID-19.

Explosive, Chemical, and Pathogen Detection

Current detection of explosives, narcotics, toxins, pathogens, and chemical or biological warfare agents is often conducted through swipe sampling from surfaces, a process that can be both difficult and dangerous. NRL conducts a broad program of basic and applied research to generate new Navy technologies and warfighter protection capabilities to identify these substances in a safer and operationally effective manner.

One thrust of NRL's current and future research is directed at optical chemical signature detection conducted at a distance, such as through a handheld camera or helmet-mounted display. Having already pioneered Infrared Backscatter Imaging Spectroscopy (IBIS) technology, which uses lasers and an IR camera to interrogate a surface, NRL seeks to improve IBIS's operational performance and affordability. Continued improvements will enhance the protection for warfighters and other security personnel.

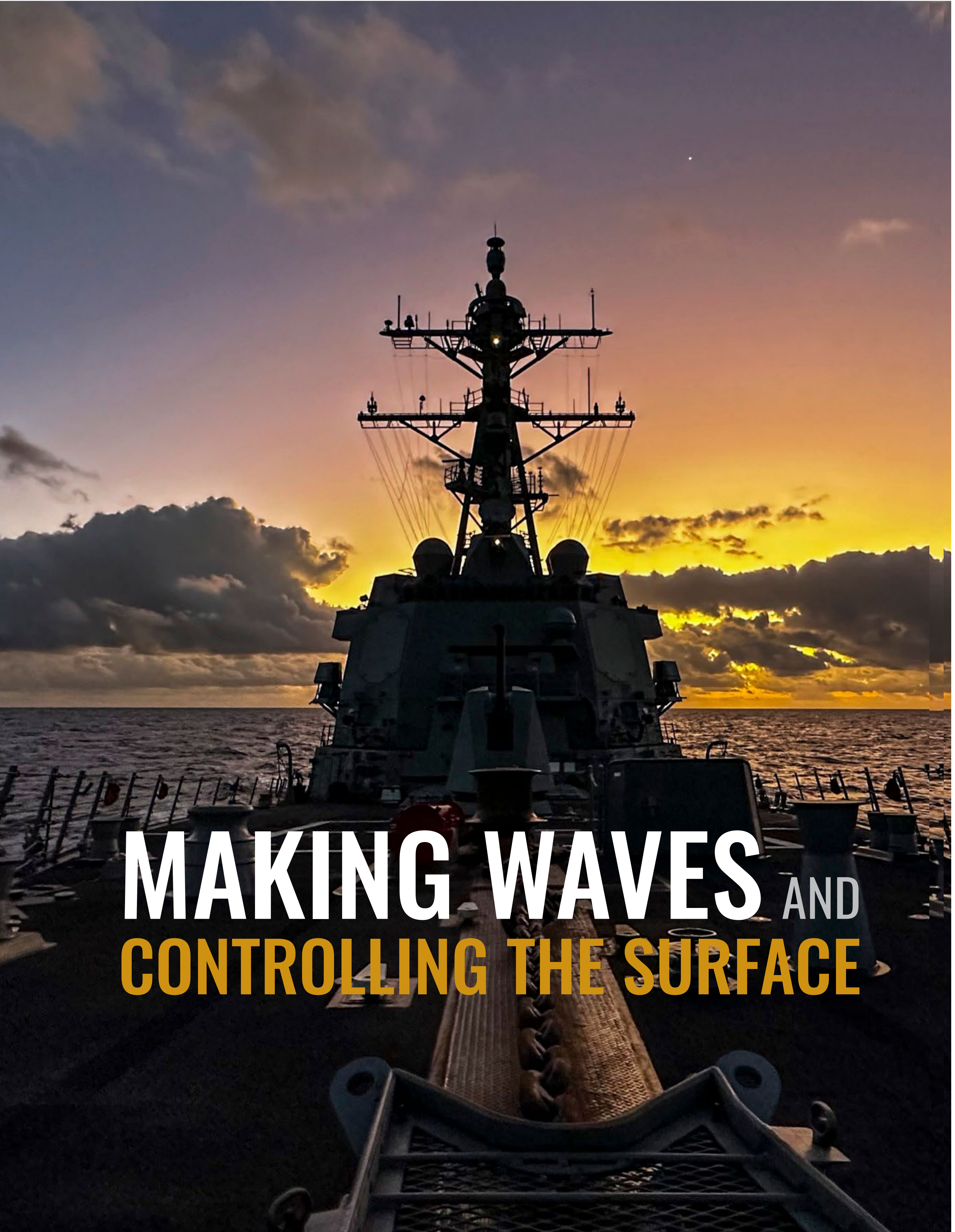


Photo by MC2 Colby A. Mothershead

MAKING WAVES AND CONTROLLING THE SURFACE

THE NAVAL RESEARCH LABORATORY HAS BEEN AT THE FOREFRONT OF SURFACE WARFARE INNOVATION FOR THE PAST 100 YEARS.

It was, in fact, the sinking of a ship that led directly to the first call for the organization that would become NRL. After the loss of RMS Lusitania in 1915, Thomas Edison wrote in the New York Times that "the Government should maintain a great research laboratory . . . in [which] could be developed . . . all the technique of military and naval progression without any vast expense."

The Secretary of the Navy seized upon the suggestion and began the process of establishing the Naval Research Laboratory. Since 1923, from weapons systems to reconnaissance to weather forecasting to advanced fuel production, NRL's research and development continues to be a critical element in maintaining the strategic advantage of the United States at sea.

Surface Acoustic Wave Chemical Sensors

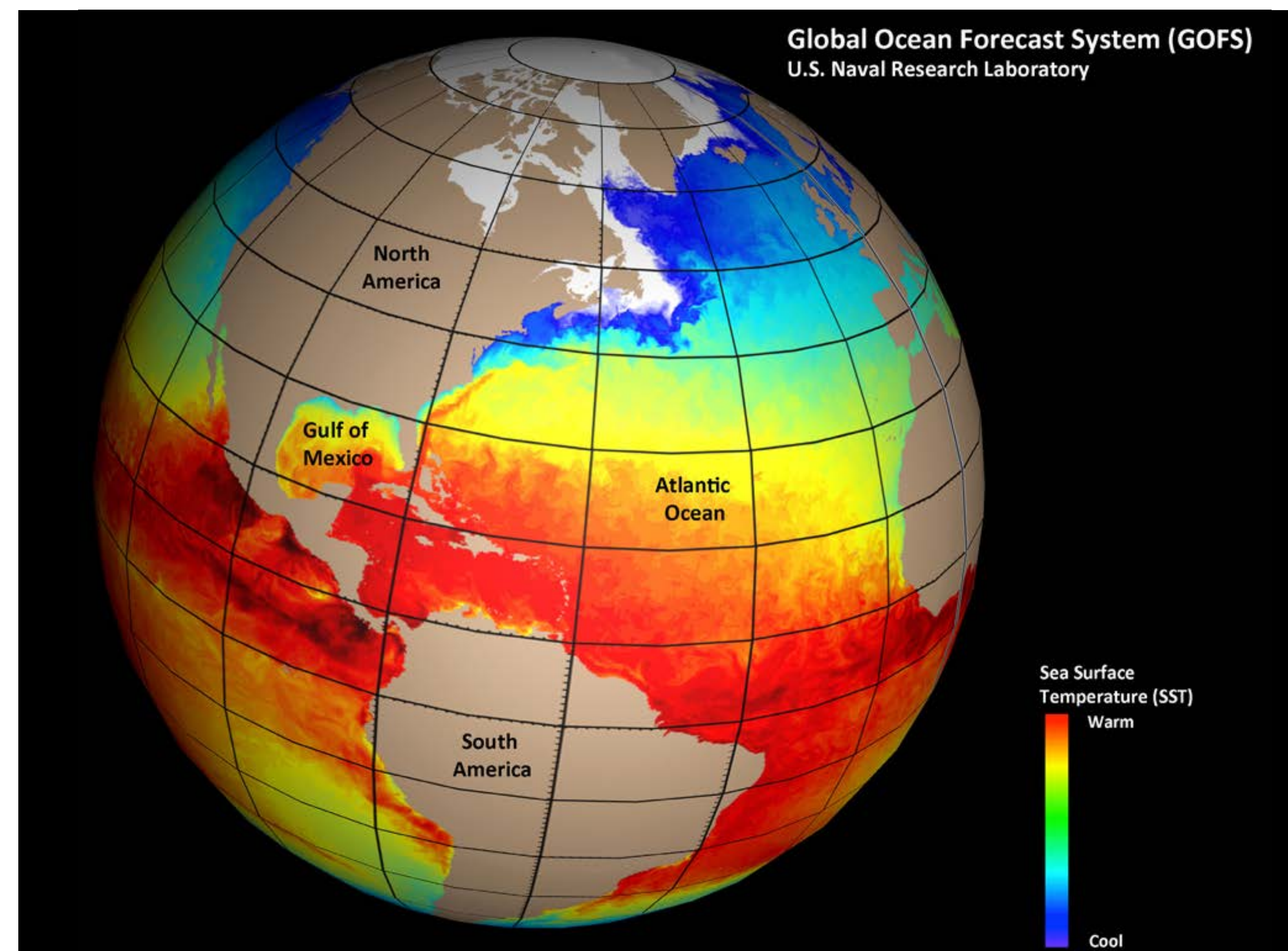
NRL has spearheaded the use of surface acoustic wave (SAW) technology to detect chemical vapors and warfare agents.

Since the 1980s, NRL's research and development of SAW sensor arrays has provided significant capabilities for warfighters and homeland defenders to analyze and detect potentially deadly threats. NRL SAW sensor systems have been used at the 1996 Olympics, during Operation Iraqi Freedom, and across the commercial sector.

Global Ocean Forecast System

The Global Ocean Forecast System (GOFS) is the Navy's global ocean prediction system that runs daily at Naval Meteorology and Oceanography Command production centers. The first global system was declared operational in 2006 as GOFS 2.0 and was based on two NRL-developed ocean models, the Navy Layered Ocean Model (NLOM) and Navy Coastal Ocean Model (NCOM).

GOFS 3.0 became operational in 2013 and represented a next-generation forecast system based on the Hybrid Coordinate Ocean Model (HYCOM) developed under an Office of Naval Research-sponsored consortium



The Global Ocean Forecast System (GOFS) is the Navy's global ocean prediction system that runs daily at Naval Meteorology and Oceanography Command production centers. The first global system was declared operational in 2006. NRL graphic between NRL and academia. GOFS 3.1 was declared operational in 2018 and has been further developed to GOFS 3.5.

GOFS provides the Navy with a first look of the three-dimensional ocean environment "anywhere, anytime" across the global oceans as well as the icy poles, providing critical forecasts for tactical planning, optimum track ship routing, search and rescue operations, long-range weather prediction, and the location of high-current shear zones.

Tactical Reconnaissance Technology for Coastal Ocean

NRL's Hyperspectral Imager for the Coastal Ocean (HICO) is a spaceborne sensor flown on the International Space Station. HICO demonstrated the utility of hyperspectral imaging for the study of the world's coastal oceans, lakes, and inland waterways.

The sensor operated nearly continuously from 2009 through 2014, collecting approximately 10,000 images and greatly exceeding the design lifetime. The data provided by HICO addressed many aspects of the ocean environment that affect naval operations.

First Operational Shipboard Laser Weapon

Challenges posed by asymmetric warfare and hypersonic missiles are placing new demands on the Navy. These threats create the need for defensive weapons that have a low cost –per shot, offer a deep magazine, and are high-precision, high-speed, and compact in size. An early response to these warfighting requirements was the first operational shipboard laser, the Laser Weapon System (LaWS), the result of collaborations between NRL, the Naval Surface Warfare Center, Pennsylvania State University, and industry.

In 2014, LaWS was installed aboard USS Ponce (AFSB (I) 15) to test the viability of directed-energy weapons in an operational environment. It was soon declared an operational asset and the ship's commander was given permission to defend the ship with the weapon.

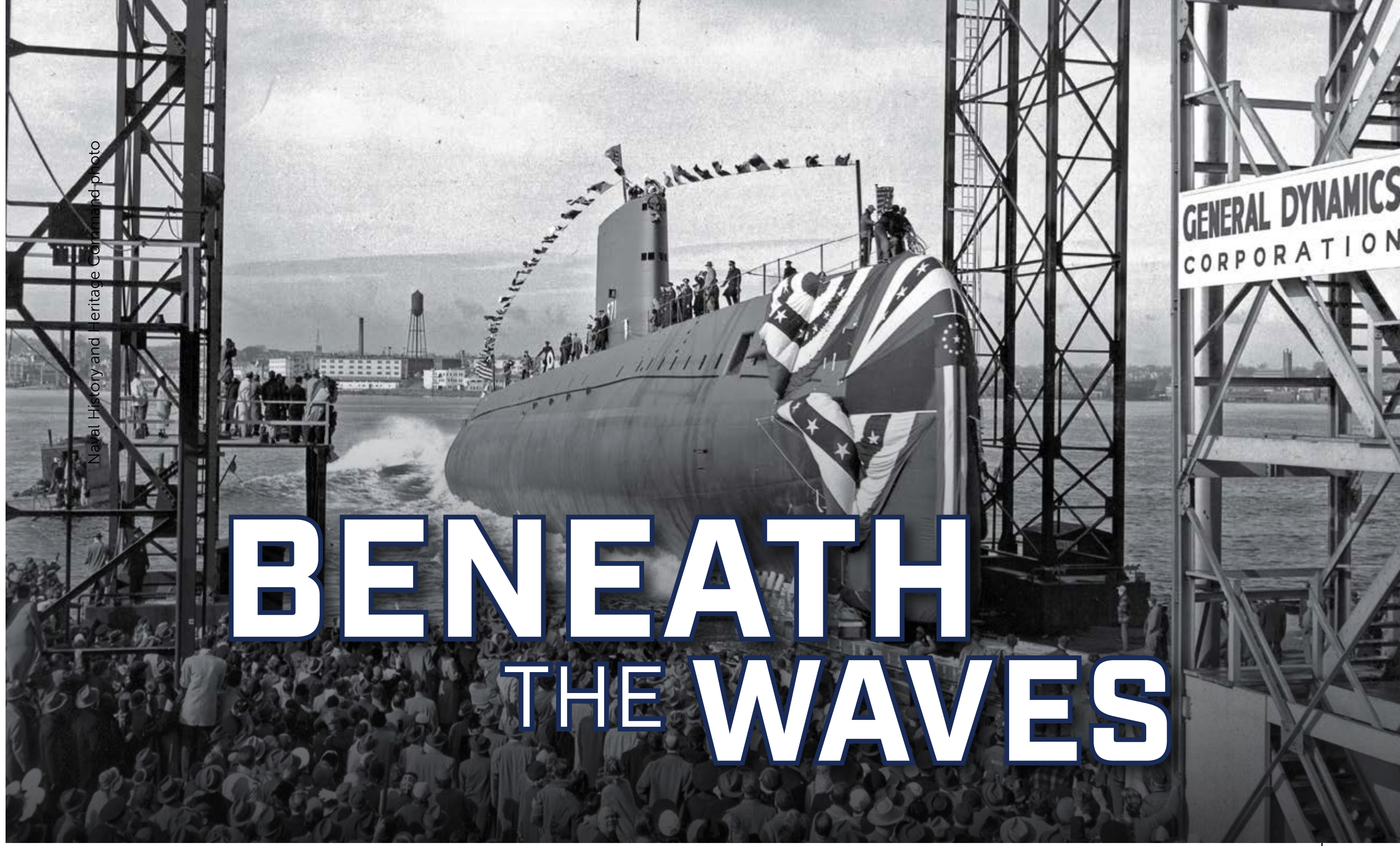
Each shot from the prototype laser costs 59 cents. In contrast, the SM 2, a common surface-to-air weapon, costs the Navy roughly $400,000 per missile. LaWS is considered effective against a range of threats including unmanned aerial vehicles, slow-moving helicopters, rigid-hull inflatable boats, fast patrol craft, as well as multiple small boats in swarm attack formations. With lasers supplementing missiles and other shipboard weapons, ships would be able to remain at sea longer without the need for ordnance reloads.

In 2014, the first operational naval laser weapon system was installed aboard USS *Ponce* (AFSB (I) 15) to test the viability of directed-energy weapons in an operational environment. Photo by John F. Williams

Clean Fuel from Seawater

The US military is the world's largest buyer and consumer of petroleum-derived fuel. An increase in global fuel demand, reduction in availability, cost fluctuations, and dependence on vulnerable foreign fuel sources are all potential threats to US military operational capabilities that could result in decreased operational flexibility and sustainability. In addition, the ability to replace petroleum-based fuel with a carbon-neutral fuel would provide significant environmental benefits. The ability to produce replacement fuel at or near the point-of-use could provide a great military advantage as well.

In response to these challenges, NRL has pioneered a forward-deployable capability to generate fuel when and where it is needed from CO2 and hydrogen found in seawater. The NRL electrolytic cation exchange module (E-CEM*) is a direct ocean capture process that removes both dissolved and chemically bound CO2 from seawater so that carbon neutral liquid fuel can be produced. Current work focuses on scale-up from laboratory to production quantities. In 25 years, large-scale production of carbon neutral liquid fuel from seawater might provide the navy access to clean energy wherever and whenever required, including areas of forward operations.



Naval History and Heritage Command photo

BENEATH THE WAVES

NRL WAS THE FIRST TO PROPOSE THE IDEA FOR BUILDING A NUCLEAR-POWERED SUBMARINE, A TECHNOLOGY THAT WOULD REVOLUTIONIZE NAVAL WARFARE. SINCE ITS INCEPTION, NRL HAS BEEN AT THE FOREFRONT OF RESEARCH AND DEVELOPMENT OF UNDERSEA TECHNOLOGY.

It NRL's legacy in the undersea domain is perhaps best characterized by its first proposal and development of nuclear submarine technology, but it also includes an early fathometer, the first sonar, and many critical mapping and forecasting technologies. NRL's pioneering role has shaped the fleet and helped create some of the world's most advanced undersea systems.

First Operational Fathometer

In 1925, NRL developed the first American naval fathometer, which measured the ocean's depth using sound waves. It was a revolutionary improvement over previous methods, which relied on dropping weighted lines to measure depth. The fathometer allowed for more accurate ocean floor mapping and made it much easier and safer to navigate ships in shallow waters.

NRL's "Sonic Depth Finder" was the first ocean depth-sounding fathometer to be installed for routine service in surface vessels and submarines of the US Navy. Its use greatly enhanced surface and subsurface navigation and surveying. NRL's research and development of fathometers improved ship safety, protected sailors, and gave the United States an immense strategic advantage in both military and commercial ventures.

First Proposal for a Nuclear Submarine

The use of nuclear power to propel submarines underwater was first proposed by NRL physicist Ross Gunn in 1939. While the discovery of fission led many toward weapons research, NRL was one of the first to see its potential for propulsion.

The resultant work quickly broke new ground in nuclear research, with NRL scientists developing methods of nuclear energy production that were later used by the Manhattan Project, and that are still used today. Although, at the time, the main thrust of government resources went toward the development of the atomic bomb, NRL was the first to conceive, propose, and investigate the use of nuclear power in submarine propulsion.

In 1946, NRL composed a report entitled "The Atomic Energy Submarine," which concluded that it was indeed feasible to construct reactors of a size and output suitable for ship propulsion. In 1954, the world's first nuclear submarine, the USS *Nautilus* (SSN 571), was launched. To this day, the nuclear powered submarine is one of the most formidable weapon systems ever developed.

First Operational American Active Sonar

NRL developed the first operational American active sonar system in 1939, allowing ships to detect and track submerged submarines. The system used high-frequency sound waves to locate underwater objects, providing a critical tactical capability for the Navy during World War II and beyond.

The development of the submarine in the years prior to World War I turned the attention of the world's navies towards undersea warfare. This deadly new weapon could barely be detected, nor countered, until NRL's Sound Division took on the challenge and created a sonar system.

Submarine Habitability

In the early days of submarines, conditions onboard were harsh, with cramped spaces, poor air quality, and limited provisions. From its beginning, NRL has conducted extensive research on submarine habitability, developing improvements in air conditioning, ventilation, and other essentials to enhance the quality of life for submariners.

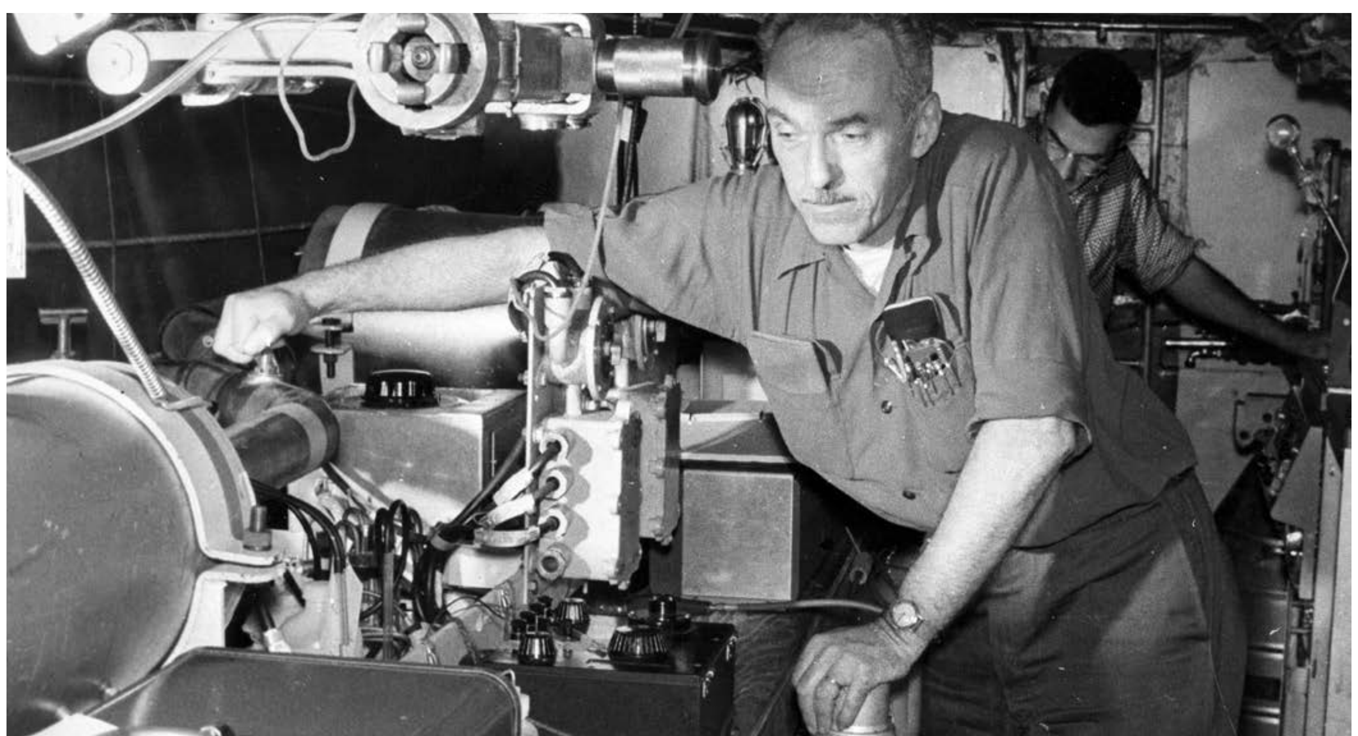
In the 1950s, as the age of the nuclear submarine emerged, the need for new habitability capabilities grew even more evident. In 1956, NRL scientists participated in a cruise aboard the first nuclear submarine, Nautilus, and found the atmosphere to be filled with a wide variety of pollutants.

Over the ensuing decades, NRL developed many different technologies to solve this problem, including the CO/H2 Hopcalite burner, the monoethanol amine CO2 scrubber, an adsorbent carbon bed, and various analytical instruments to monitor contaminants. Combined, these technologies enable the Navy to operate its submarine fleets on extended deployments while assuring of the safety of their crews.

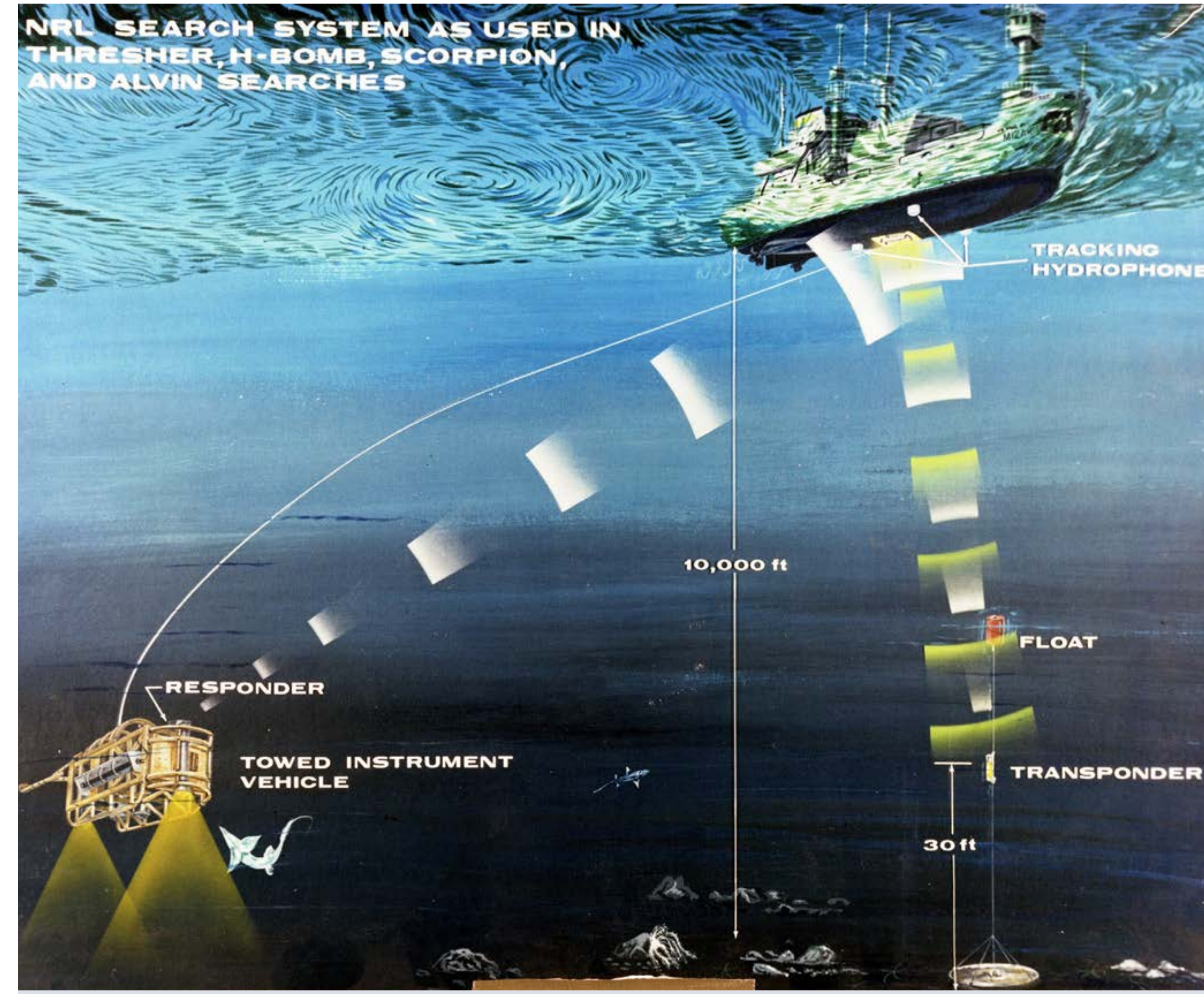
Structural Acoustics Deep Ocean Search

In the 1960s, NRL developed the Structural Acoustics Deep Ocean Search (SADOS) system, which used acoustic signals to locate and map underwater structures such as oil rigs, pipelines, and shipwrecks. The system provided critical information for underwater search and rescue operations.

In recent years, NRL has also applied this technique to mine hunting, using new broadband acoustic sources on autonomous underwater vehicles. This NRL technology also provides a high-performance capability for the detection and classification of diesel submarines using an automated approach to achieve target-clutter separation, greatly enhancing the Navy's ability to conduct undersea warfare without creating an entirely new system.



Since the rise of nuclear submarines, which can remain submerged for many weeks, NRL has developed many different technologies to solve problem of carbon dioxide build up, including burners, scrubbers, and absorbers, as well as various analytical instruments to monitor contaminants. NRL photo



The NRL-developed Side-Looking Sonar (SILOS) sled, or "fish," was deployed aboard USS *Mizar* (T-AGOR 11) as part of several major undersea search expeditions during the 1960s, including the discovery of the lost submarines USS *Thresher* (SSN 593) and USS *Scorpion* (SSN 589). NRL graphic

Coordinated Autonomous Underwater Vehicle Sonar Operations

Recent NRL breakthroughs based on acoustic sonar technology, underwater system autonomy, artificial intelligence, compact energy sources, and underwater acoustic communications will enable long-duration, unmanned, coordinated underwater sonar operations, with multiple autonomous underwater vehicles (AUVs).

Such unmanned and nonoperator controlled fleets will provide the Navy with significantly increased sonar capabilities in antisubmarine warfare, mine countermeasure operations, and counter-AUV missions. Such a capability will also support affordable comprehensive diagnostic exercises to characterize and reduce the acoustic vulnerability of the Navy's own underwater assets.

Ocean Acoustic Prediction

NRL continues to lead the research and development of undersea warfare technology, and it continues to pursue advanced ocean acoustic prediction models to enable the Navy to predict the behavior of sound waves in the ocean accurately. These models will provide an enhanced critical capability for submarine operations, improving their ability to navigate stealthily and accurately detect other underwater objects.

Current and future work at NRL, on ocean acoustic prediction models will ensure the United States remains at the forefront of undersea warfare technology, and ensure the Navy's continued superiority in the undersea domain.

Naval History and Heritage Command photo

SUPERIORITY IN THE SKY

NRL CONTRIBUTIONS TO AIR WARFARE INCLUDE THE DEVELOPMENT OF THE FIRST AMERICAN AIRBORNE RADAR, SUCH AS THIS ASB SYSTEM ON THE STARBOARD WING OF A WORLD WAR II HELLDIVER AIRCRAFT.

NRL has long been at the forefront of innovation in air warfare technology. NRL's advanced testing techniques and facilities led to the development of the first American airborne radar and continue to provide warfighters with a critical edge through next-generation unmanned aerial vehicles (UAVs), reconnaissance systems, countermeasures, and more.

Aerodynamics Modeling and Simulation

In the 1920s, NRL pioneered the development of aerodynamics modeling and simulation, allowing for more efficient aircraft design. These advances were crucial to developing US airpower during World War II.

This innovative work continues and is spearheaded by NRL's development of new aerodynamic research facilities that provide mission-critical capabilities testing for a wide range of military aircraft.

First American Airborne Radar

At the outset of World War II, NRL developed the first American airborne radar, called the Model ASB. The Model ASB was expected to primarily counter enemy submarines, but its effectiveness led to extensive use in bombing missions, ship detection, and airborne intercepts.

It was widely employed by the Navy and Army Air Forces as well as by British Commonwealth allies. It was installed almost universally in Navy aircraft and became known as "the Workhorse of Naval Aviation." Nearly 26,000 units were procured, the largest procurement of any model radar. It is generally considered to be one of the most successful of all airborne radars ever developed.

Radar Absorbing Materials and Anechoic Chambers

In 1945, NRL developed the "NRL Arch" apparatus to test the performance of broadband radar absorbing materials. The NRL Arch is still used by materials manufacturers and stealth technology contractors around the world.

NRL developed DARKFLEX in 1953, a precursor to materials used in today's radar anechoic chambers, and also built the world's first effective anechoic chamber the same year. The design principles employed by NRL are still used in most modern chambers. NRL's work pioneered stealth technology and significantly affected its use in submarines, missiles, aircraft, ships, and land vehicles.

Fixed-wing Airborne Gravimetry

NRL developed the first airborne gravimetry system in the 1960s that enabled more accurate mapping of the Earth's gravitational field, which proved critical in particular for submarine navigation.

In 1979, NRL began a program in airborne gravimetry from long-range, fixed-wing aircraft capable of meeting Navy requirements. The program required the development of highly accurate three-dimensional aircraft positioning, specialized aircraft operational techniques, and improvements to gravimeter technology.

NRL's long-range airborne gravity measurement system has provided vital data for the Navy and other DoD tactical and strategic systems that cannot be acquired in any other way. Airborne gravity data are collected worldwide to support operations for submarines, ballistic missiles, and aircraft. In other uses, fixed-wing airborne gravimetry was deployed in Afghanistan for strategically critical, airborne, remote-sensing and -mapping projects conducted jointly by NRL and the US Geological Survey under the name Rampant Lion.

AN/ALE-50 Towed Countermeasures

In the 1990s, NRL developed the AN/ALE-50 towed countermeasures system, which provided a critical capability for aircraft self-defense. Improving aircraft survivability, the system deployed decoy-flares to distract and confuse enemy missiles. The AN/ALE-50 was the first towed decoy to be used as an in-flight countermeasure.

The AN/ALE-50 decoy is designed to look more like an aircraft than the aircraft itself to hostile systems. Since the 1990s, more than 25,000 decoys have been delivered for use on the F-16, F/A-18E/F, and B-1B aircraft. NRL photo

The towed decoy concept differs from the traditional goals of electronic warfare, in which anti-aircraft missiles are denied the information needed to launch and intercept. Instead, the towed decoy's effectiveness lies in looking more like an aircraft than the aircraft itself to hostile systems.

Over the years, the AN/ALE-50 has surpassed expectations at every stage of its development. More than 25,000 decoys have been delivered for use on the F-16, F/A-18E/F, and B-1B aircraft. At a relatively modest cost of $22,000 per decoy, it reduced the effectiveness and negated the threat of billions of dollars in opponents' advanced antiaircraft systems.

This decoy protects combat aircraft so well that it has earned the nickname "Little Buddy" from American pilots. In the Kosovo campaign alone, 1,479 were used and the system was credited with saving several aircraft.

Dragon Eye

In the 1990s and 2000s, NRL developed an affordable and expendable airborne-sensor platform, Dragon Eye, to provide reconnaissance capabilities to small units of Marines, to assess battle damage, to detect threats over the next hill or around the next building, and to prevent casualties from friendly fire.

Dragon Eye was developed from a paper sketch to an operational system in only 30 months: prototype evaluation began in 2001 and production aircraft were deployed in Iraq and Afghanistan by 2004. This hand-launched vehicle was transported by a single warfighter, had the radar signature of a bird, and provided essential knowledge in the most dangerous environments.

Reconnaissance Systems

NRL has developed advanced reconnaissance systems since its inception, including the first airborne radar system and the first reconnaissance satellite. These systems have provided the US military with critical intelligence and surveillance capabilities.

The F/A-18 Shared Reconnaissance Pod (SHARP) is a digital reconnaissance system developed by NRL to replace the aging, film-based F-14 Tactical Airborne Reconnaissance Pod System (TARPS). SHARP provides high-resolution visible and infrared digital imagery from medium and high-altitude cameras.

The NRL-developed Reconnaissance Management System enables real-time compression, on-board storage and manipulation, and off-board dissemination to ground- and sea-based forces in real-time using wide-band radio links. In addition, NRL-developed ground station technology is used to receive and exploit the SHARP imagery.

The first SHARP production systems were deployed in Operation Iraqi Freedom, Operation Enduring Freedom, and Operation Tomodachi.

Hybrid Tiger UAV

In 2011, NRL developed the Hybrid Tiger UAV, demonstrating the feasibility of using a hybrid electric-and-gas propulsion system for unmanned vehicles. Hybrid Tiger represented a significant advancement in UAV technology, providing longer endurance and improved performance than vehicles of comparable size and weight.

Hybrid Tiger can fly for 24 hours or more despite extremely adverse conditions. NRL plans to demonstrate its maximum endurance with a 48+ hour flight with a payload while consuming no logistics fuel. While Hybrid Tiger was developed and demonstrated to meet DoD's requirements, its technologies are also valuable for scientific applications such as atmospheric research and commercial ventures.

In 2011, NRL developed the Hybrid Tiger unmanned aerial vehicle, demonstrating the feasibility of using a hybrid electric-and-gas propulsion system for unmanned vehicles. NRL photo

NRL photo

SPACE RESEARCH AND TECHNOLOGY

OVER THE PAST CENTURY, NRL RESEARCHERS CREATED MANY NEW RESEARCH AND DEFENSE MISSION TECHNOLOGIES, WITH SOME LEADING TO GROUND-BREAKING INVENTIONS THAT 21ST-CENTURY SOCIETY TAKES FOR GRANTED, AND OTHERS THAT SET STANDARDS FOR "FASTER, BETTER, AND CHEAPER" SPACE DEVELOPMENT.

Throughout the Space Race in the mid-20th century, no American government agency other than NASA has been more impactful than NRL. Over the past century, NRL researchers created many new research and defense mission technologies, with some leading to ground-breaking inventions that 21st-century society takes for granted, and others that set standards for "faster, better, and cheaper" space development. NRL is poised to develop new breakthroughs in satellite development, spacecraft materials technology, and space-based intelligence and communications in the coming years.

First Far-Ultraviolet Spectrum of the Sun

In 1946, using a captured German V-2 rocket, NRL scientists obtained the first far-ultraviolet spectrum of the Sun from beyond the Earth's atmospheric boundary. The rocket carried cosmic ray detectors, pressure and temperature gauges, radio transmitters, a spectrograph, and antennae to measure propagation through the ionosphere.

Although earlier flights had returned scientific data revealing cosmic-ray counts and pressure and temperature information, the first successful retrieval of an ultraviolet spectrum of the Sun captured the attention of both the scientific community and popular press. This achievement also marked the birth of space-based astronomy, as well as the Navy's space program.

Viking Rocket Sounding Program

In 1946, NRL developed the Viking sounding rocket, which was the first rocket designed specifically for research purposes and the first to use attitude control, provided by an NRL-designed gimbaled motor for steering and intermittent gas jets for stabilizing the vehicle after main power cutoff. These attributes are now used extensively in large steerable rockets and space vehicles. The Viking engine was one of the first large liquid-propelled rocket engines produced in the United States.

NRL launched a total of 14 Viking rockets between 1949-57. Viking 4 demonstrated that such a rocket could be handled and operationally launched from a ship, a major step toward the eventual deployment of missiles at sea. In 1954, Viking 12 (on display at the Smithsonian Air and Space Museum) reached 144 miles' altitude, where it took what at the time was the highest altitude photographs of the Earth.

Methods for tracking, telemetering data, and designing rockets have all been honed during NRL's decade of sounding rocket research. In many ways, Viking paved the way for the historic Vanguard project, America's first satellite program. Even today, sounding rockets remain a critical platform used to establish the space readiness of satellite instruments, and continue to be vital for upper atmospheric research.

First Detection of X-Rays from the Sun

With the launch of an experiment aboard a V-2 rocket in September 1949, NRL confirmed that X-rays from the Sun are a principal cause of ionization in the E region of the Earth's ionosphere. Additional experiments, aboard a Viking flight and two Aerobee sounding rocket firings, later indicated that the solar X-ray spectrum is adequate to account for all of E-layer ionization.

This pioneering research contributed profoundly to the understanding of the physical processes in the solar atmosphere, including an increased understanding of the effects of solar disturbances on radio communication, and an improved ability to predict the influence of solar particle emissions on the radiation environment of manned space flight. NRL researcher Herbert Friedman received the National Medal of Science, the highest American honor for scientific achievement, for leading this work.

In 1946, NRL developed the Viking sounding rocket, the first rocket designed specifically for research purposes and the first to use attitude control. A total of 14 Viking rockets were launched by NRL between 1949-57. NRL photo

NRL's increasingly refined understanding of the ionosphere has aided and contributed to improvements in naval communications on Earth and in space, missile and satellite tracking, telemetering of data from rockets and satellites, predicting the effects of ionospheric scintillation on GPS satellites, and it also played a crucial role in the operation of high-frequency direction finder systems used to track Soviet submarines. .

Vanguard

Between 1955 and 1959, NRL established the first American satellite program, Vanguard. Leveraging successes with the Viking program, NRL was selected to design, build, launch, place into Earth orbit, and track an artificial satellite carrying a scientific experiment. On March 17, 1958, Vanguard I became the fourth satellite successfully launched into Earth orbit, achieving the highest altitude of any artificial vehicle at that time and meeting the program's objective of establishing a scientific satellite into orbit.

Vanguard I achieved several scientific landmarks, such as initiating miniaturized circuits and carrying two radios and a temperature sensor, and it was the first satellite to use solar cells as a power source. Vanguard I has been orbiting Earth for 65 years, and is the oldest artificial satellite. It will remain in orbit well into the 22nd century.

NRL engineers place Vanguard 1 atop the third stage of the launching vehicle. On 17 March 1958, Vanguard 1 started its historic journey into space. NRL photo

The rocket technology pioneered by Vanguard was used by later programs. One of America's most versatile and reliable launchers, the Delta rocket, reflects much of Vanguard's design.

X-Ray Astronomy

NRL's X-ray astronomy program dates back to the launch of an X-ray detector on a V-2 rocket in 1949. Over a period of three years, NRL conducted a series of sounding rocket experiments that demonstrated the discrete nature of the X-ray sources, and their association with the Milky Way. The data obtained showed that the diffuse X-ray background was cosmic in origin, and subsequently led to the detection of the first extragalactic X-ray source, through study of the Crab Nebula, and provided the first observational evidence for the X-ray production mechanism.

Soon after, NRL produced a sky map of galactic and extragalactic emitters, the HEAO A-1 X-Ray Source Catalog, which included 842 discrete X-ray sources, which became a standard reference source for galactic and extragalactic X-ray emitters.

The work by NRL researchers was critical to X-ray astronomy, contributing to the development of a new and important research specialty. X-ray research has made important contributions to the advance of cosmology and astrophysics.

SOLRAD I

NRL's Solar Radiation (SOLRAD) program was conceived in the late 1950s as an improved means of studying the Sun's effects on the Earth. Of prime interest was the effect of solar radiation on the ionosphere, which has critical importance to naval communications. It was one of the nation's longest continuing series of satellite projects dedicated to a specific research program. SOLRAD I was launched in June 1960, with ten more SOLRADs built by NRL and flown through 1976.

The SOLRAD satellites monitored the Sun for more than 15 years, providing not just valuable real-time observation and warning, but also archiving for generations scientific information on many types of high-energy flares and the Sun's effects upon the Earth's atmosphere. The new knowledge gained by the program also yielded practical, and in some cases critical, benefits to naval communication and the US manned space program.

America's First Operational Intelligence Satellite

In June 1960, 52 days after a U-2 aircraft was lost on a reconnaissance mission over the Soviet Union, the NRL-developed GRAB I satellite soared into orbit and began transponding space-intercepted electronic intelligence signals to Earth-bound signals intelligence stations. GRAB I was America's first operational intelligence satellite.

The GRAB project provided proof-of-concept for satellite-collected electronic intelligence. This was accomplished by demonstrating that a platform in outer space could collect as much as all other sea, air, and land-based reconnaissance platforms, at a fraction of their costs, and with no risk to personnel. Before GRAB, such information could not be obtained by airborne reconnaissance or without enormous risk to human sources. The intelligence information gained from GRAB I profoundly impacted national security decision-making and contributed to deterrence of nuclear conflict with the Soviet Union.

Launched on 17 March 1958, Vanguard 1 was the second American satellite placed in orbit, the culmination of years of effort by the Naval Research Laboratory. Its electronics silent since 1964, Vanguard 1 remains in orbit and is the oldest man-made object in space. NRL photo

TIMATION and NAVSTAR GPS

The NAVSTAR Global Positioning System (GPS) changed the world. NAVSTAR is based on NRL's TIMATION (Time/Navigation) research program, which began in 1964 and was designed to provide precise navigation data to military and civilian users using a constellation of 24

satellites. The TIMATION program proved that a system using a passive ranging technique and highly accurate clocks could provide the basis for a revolutionary navigation system with three-dimensional coverage (longitude, latitude, and altitude) worldwide.

NAVSTAR's military and commercial applications are too numerous to count. In 1993, the National Aeronautic Association selected the GPS team composed of NRL, the US Air Force, Aerospace Corp., Rockwell International, and IBM Federal Systems Co. as winners of the 1992 Robert J. Collier Trophy, the most prestigious of all aviation awards in the United States. The citation accompanying the trophy honors the GPS Team "for the most significant development for safe and efficient navigation and surveillance of air and spacecraft since the introduction of radio navigation 50 years ago."

Spaceborne Solar Coronagraphs

With the advent of space-based instrumentation, observations of the Sun's corona—its outermost atmosphere—became far more effective. The first coronagraph for this purpose was developed and launched on a sounding rocket by NRL in 1963. Its success gave birth to a new understanding of the solar atmosphere.

In 1971, an NRL coronagraph, on NASA's OSO-7 satellite, captured images of an immense explosion of solar material moving through the instrument's field of view. The phenomenon was a major new discovery, of what would be named, a coronal mass ejection. The measured speed of the outburst was about 600 miles per second, and its estimated size was many times the size of the Earth. The frequency and the space weather impact of such events was established by NRL's SOLWIND coronagraph, which launched in 1979. SOLWIND led to the Large Angle and Spectroscopic Coronagraph (LASCO), which was jointly developed for the ESA-NASA Solar and Heliospheric Observatory (SOHO) mission by NRL and labs in Europe. Launched in 1995, SOHO verified that coroneal mass ejections produce geomagnetic storms at Earth, explained the relationship between flares and ejections, and established the magnetic flux rope as the probable configuration. LASCO still operates today and helps to predict mass ejection arrival times at Earth.

Spaceborne solar coronagraphs are now essential to space weather models of mass ejections, which are disruptive of communications, power, and military detection systems. If these storms are severe, astronauts and equipment in space can be at risk. NRL's scientific discoveries have provided immense benefits and continue to protect aspects of life and materiel on Earth and in space

Clementine

The Deep Space Program Science Experiment (Clementine) was a successful lunar mapping mission. NRL was responsible for mission design, spacecraft engineering, spacecraft manufacture and testing, launch vehicle integration, terrestrial support, and flight operations.

In 1994, NRL put this satellite with a sensor payload into orbit around the Moon. A high-quality mapping mission of the lunar surface included a complete imaging of the lunar surface (1.8 million images) in 11 discrete wavebands with coarse altimetry over most of the surface.

This imaging of the Moon's surface was a great success in its scientific returns, and Clementine's images were made available for students everywhere to explore in a 3-D interactive environment online.

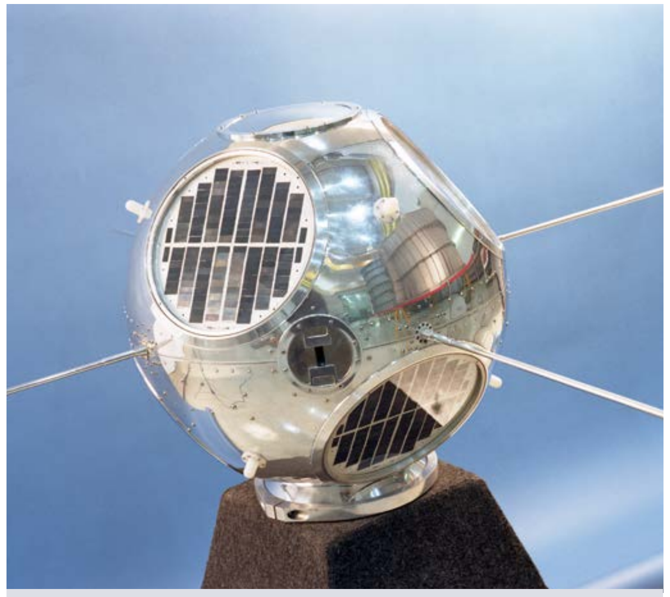
With Clementine's success, the United States returned to the Moon for the first time since the end of the Apollo lunar missions. NRL's satellite demonstrated that the goal of "faster, better, cheaper" space technology was attainable: Clementine was built in only 22 months (less than half the usual time) for one fifth of the typical cost for similar space probes. The probe was so easy to operate that its mission control center comprised eight engineers in a warehouse in Alexandria, Virginia.

Robotic Servicing of Geosynchronous Satellites

Satellites perform critical missions for national defense, science, and commerce. Without servicing technology, these high-value vehicles are not inspected, maintained, or upgraded after launch. NRL's Robotic Servicing of Geosynchronous Satellites (RSGS) is poised to bring revolutionary benefits to U.S. space capability, making satellite servicing a reality.

This emerging national space capability promises to usher in a new era of United States space superiority where satellites can be maintained, upgraded, and repaired, are made more resilient and cost-effective, and can be assembled in space, no longer limited by the launch capabilities of a single rocket. Satellites will no longer need to be disposed of when they approach end-of-life, experience potentially repairable problems, or no longer meet their defense, scientific, or market needs.

This innovation is only possible with the 20-plus years of research, technology maturation, and infrastructure creation at NRL. The RSGS program is scheduled to launch an operational robotic servicing vehicle to geosynchronous orbit in 2025.



The GRAB project, the first operational intelligence satellite, provided proof-of-concept for satellite-collected electronic intelligence. GRAB demonstrated that a platform in outer space could collect as much as all other sea, air, and land-based reconnaissance platforms more economically and safely. NRL photo

Hypersonics

Reliable hypersonic flight requires advanced research into new materials, new cooling systems, and ingenious new aerodynamic designs for hypersonic aircraft that can withstand extreme conditions and perform equally well across various operational regimes. Researchers at NRL are calling such an aircraft "a morphing wave rider."

Drawing on the original Wright Brothers observation of birds maneuvering by changing the shape of their wings, NRL aims to achieve a smooth, seamless control surface without ailerons, flaps, or hinges—and instead through morphing, allowing advanced control of the wave rider at hypersonic speeds.

X-Ray Pulsars for Timekeeping and Navigation

Currently, many spacecraft get their navigation and timekeeping information from global navigation satellite systems such as GPS. GPS is subject to disruptions and interference, however, that can degrade its availability. Consequently, alternative sources of navigation information are valuable for resilience and extending the operational domain.

Pulsars are neutron stars, born in supernova explosions, and are nature's most stable clocks. Observing their predictable signals provides a natural analog to GPS that can allow a spacecraft to autonomously determine its location, velocity and time using X-ray observations of their pulses. NRL has developed and patented the technology for autonomous navigation using X-ray pulsars, with ongoing work focused on improving the efficiency, resilience, and range of these systems.

Space Solar and Power Beaming Technology

In 2022, a team of researchers from NRL demonstrated the feasibility of terrestrial microwave power beaming by transmitting 1.6 kilowatts of power over 1 kilometer (km) at the US Army Research Field in Blossom Point, Maryland, the most significant power beaming demonstration in nearly 50 years.

Microwave power beaming is the efficient, point-to-point transfer of electrical energy across free space by a directive microwave beam. The project is known as Safe and Continuous Power Beaming-Microwave (SCOPE-M).

NRL developed this new technology within 12 months of assignment. By beaming power directly from space, US forces can dramatically reduce their reliance on traditional fuels. It is also the ultimate "green technology" that can provide continuous power all day, at any time of the year.

NRL photo

COMMUNICATIONS, INFORMATION TECHNOLOGY, AND CYBERWARFARE

NRL HAS EXCELLED IN THE FIELDS OF COMMUNICATIONS, INFORMATION TECHNOLOGY, AND CYBERSECURITY WITH CUTTING-EDGE ACHIEVEMENTS IN RADIO—SUCH AS THE FIRST HIGH-FREQUENCY RECEIVER SEEN HERE—SATELLITES, AND CYBERSPACE.

NRL's advancements in communications technology have shaped the technology of warfare as well as of civilian life. Looking toward the future, NRL will continue its proud tradition of innovation in these increasingly important fields.

Development of High-Frequency Radio Equipment

NRL's development of radio technology began in the 1920s with radio equipment, such as quartz-crystal frequency control, high-power transmitters, and receivers, which led to the adoption and extensive utilization of high-frequency (HF) communications by the Navy. These innovations enable faster, stronger, and less detectable communications.

Radio Propagation and the "Skip-Distance" Effect

In 1925, NRL discovered the principles governing the "skip-distance" effect, which could not at the time be explained

by the prevailing wave-propagation theory. The effect refers to radio signals that disappear after the "ground wave" dissipates but reappear at a considerable distance, varying with frequency, time of day, and even by season, due to reflection off something high in the atmosphere.

NRL's work in this area further demonstrated that around-the-world HF transmissions could be obtained through successive reflections from the Earth's ionosphere with the proper choice of frequency, time of day, and season. HF transmitter "backscatter" observations generated the first concept of detecting and ranging on targets over very long distances. This concept led to the later development of over-the-horizon radar by NRL.

NRL developed the world's first Linear Predictive Coder in 1973, greatly improving secure voice communications. This third-generation Secure Voice Systems-2B Subscriber Terminal Unit provided office to office communication at 2400 and 4800 bits per second. NRL photo

Aircraft Radio Homing System

When the first aircraft carriers became available in the 1920s, there quickly emerged a need for a suitable means of navigating carrier-based planes to and from carriers and air facilities ashore.

To solve this problem, NRL developed an aircraft-radio homing system that provided the primary means for aircraft to navigate back to their carriers during World War II. Because of its effectiveness, the system was installed on all aircraft carriers and used extensively in combat operations in the Pacific. The many glowing reports received from combat units and individual pilots whose lives were saved under trying circumstances attested to the importance and value of this NRL innovation.

First Operational Satellite Communication System

In the 1920s, NRL was the first to determine the frequency above which radio waves would penetrate Earth's atmosphere and propagate through outer space, making radio communication in space possible.

In 1951, NRL was the first to demonstrate that radio energy reflected from the moon was much more coherent than predicted. As a consequence, a moon circuit could be used to transmit data at a rate and fidelity adequate for radio communication. NRL then developed the key transmitter and receiver technologies that allowed for effective communication using moon circuits.

Through decades of study and effort, NRL ushered in a new age of space-based technology by developing the key methods needed for viable satellite communications.

Secure Voice Communication

In 1973, NRL developed the world's first Linear Predictive Coder (LPC) that was able to efficiently represent the entire speech spectrum. This brought about a complete upgrading of secure voice communication across the US military.

By 2005, 40,000 LPC-based Advanced Narrowband Digital Voice Terminals (ANDVT) were deployed by the Navy, Air Force, Army, allied forces, and other government agencies to support tactical secure voice communications. NRL's pioneering research was also widely adopted in the cell phone industry and is still used today.

Further NRL research also provided direct interoperability between new and legacy ANDVT phones. This breakthrough meant that legacy phones were not retired prematurely and there was no long transition period between new and legacy systems, yielding an overall cost savings of nearly $460 million.

Cryptographic Equipment

NRL's development of the Navy Key Distribution System (NKDS) substantially improved the security of cryptographic key material that is distributed throughout the Navy to communications security accounts.

Traditionally, key material was generated and distributed as unencrypted text on paper tape. This left the key vulnerable to compromise and made rapid key distribution impossible. The concept, architecture, and requirements developed by NRL for NKDS, however, changed the paradigm of key material generation, distribution, and management and became the cornerstone of the DoD key system.

Tactical Communications

In the 1990s, NRL developed three major items of tactical receiver equipment: the Multi-Mission Advanced Tactical Terminal (MATT), the Improved Data Modem (IDM), and the Joint Combat Information Terminal (JCIT). Using knowledge gained through the MATT, IDM and JCIT programs, NRL designed an interoperable communication infrastructure, InfraLynx, to provide assured communications to military commanders. The federal Center for Domestic Preparedness adopted InfraLynx. It was deployed for the 2002 Winter Olympics, weapons-of-mass-destruction training exercises, and Super Bowl XXXVII, as well as the Democratic National Convention and the G8 Summit in 2004. In 2005, US Northern Command deployed its own InfraLynx asset, which was the first to reestablish communications after Hurricane Katrina. In 2009, InfraLynx was a key communications element in a nuclear-weapons incident exercise. InfraLynx was transitioned to Honeywell International, Inc.

Flying Squirrel and Orb-weaver

Flying Squirrel is an NRL-developed software application suite that provides real-time discovery, analysis, and mapping of wireless networks, and is also capable of scanning for Bluetooth devices. Its next-generation variant, Orb-weaver, also fulfills this mission through multiple fixed sensors.

Many organizations seek the means to securely integrate wireless capabilities into their networks. In order to detect and deter unauthorized wireless activity, Flying Squirrel and Orb-weaver are currently employed throughout the DoD, the intelligence community, federal agencies, and law enforcement, with the overall goal of detecting and geolocating any wireless technology.

Onion Routing

The original Internet and Web protocols were designed without security in mind. To address this issue, NRL invented onion routing as a way to "peel off" and separate identification from routing for Internet connections. Onion routing provides confidentiality as well as authentication of the route that connections take between client and server. This crucial NRL development continues to protect American intelligence communications online.

Free Space Optics Communication

Free Space Optics (FSO) communication is the use of modulated light to transmit data through the air, similar to the use of wireless radio. The idea to use lasers as the light source for such communications has existed since the original development of lasers in the 1960s. It was not until the explosion of commercial terrestrial fiber-optic technologies and components in the early 2000s, however, that the technology became mature enough to support implementation of communications in free space.

NRL's ongoing research in FSO communications has generated the data to support decisions about operational employment, operational concepts, and acquisition of the technology for tactical use across the military. NRL's goal is to develop and verify performance of a fieldable prototype.

Quantum Computing

Information processing is ubiquitous and vital to the DoD, and any improvement in computing capability provides a military advantage. Quantum computing is an emerging technology that could help solve the most complex numerical problems.

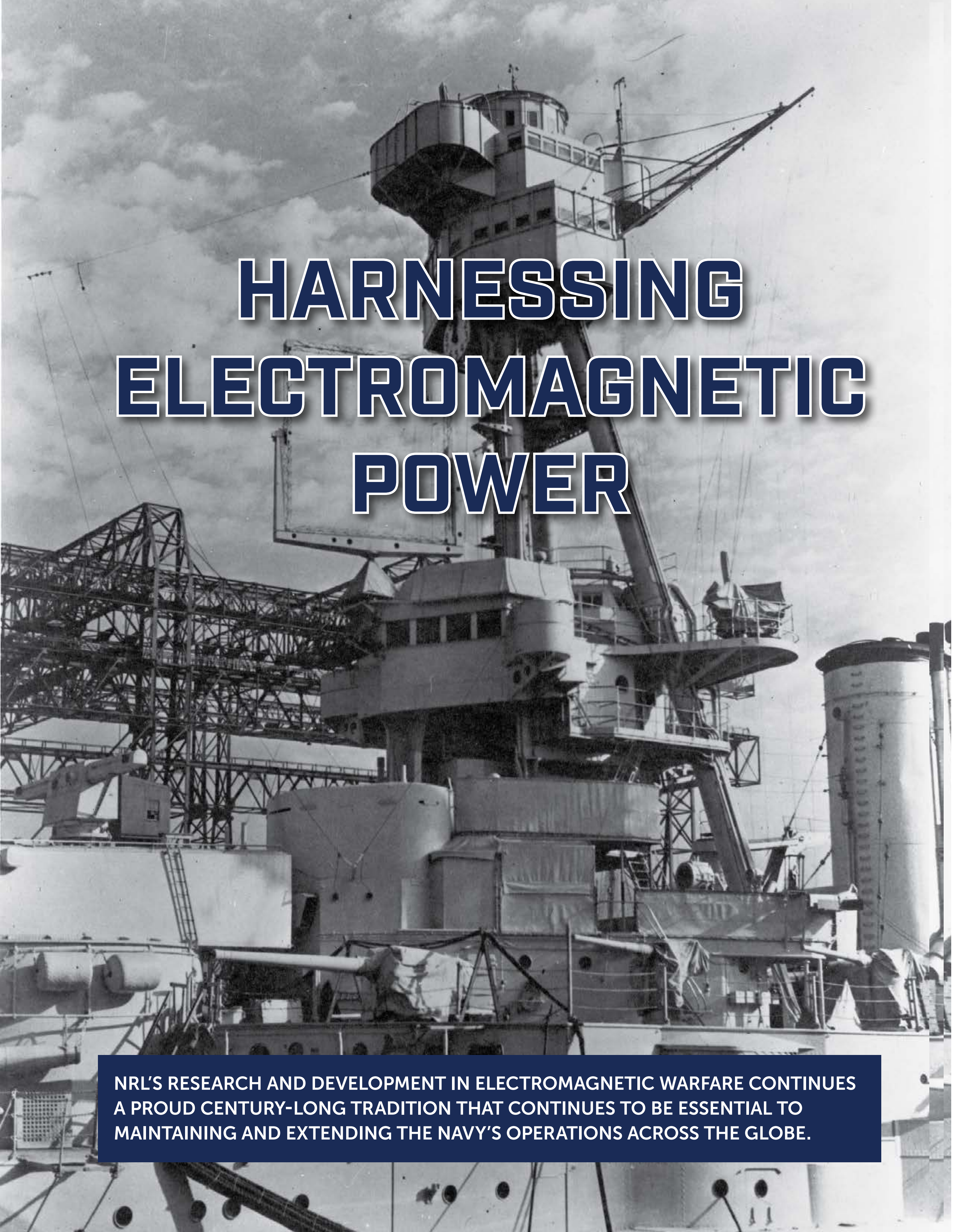
Many challenges still need to be overcome before a quantum computer can outperform a classical supercomputer. Hardware implementations need to be able to control increasingly large computational spaces, while simultaneously limiting environmental influences that cause the quantum states to lose coherence. New quantum algorithms also need to be developed to process the quantum states. NRL's ongoing research in this field is aimed at improving the materials, processes, and efficiencies of this highly promising technology.

Silicon Photonics

Silicon photonics is a branch of microelectronics that uses photons in addition to electrons. It brings light directly onto semiconductor chips that can power computers, smartphones, and defense technologies. By using advanced tools and techniques developed and matured by the microelectronics industry, whole photonic integrated systems-on-a-chip are now possible.

NRL's research is focused on DoD-specific applications of silicon photonics, especially the development of new, efficient materials and production facilities that could bring wide-ranging breakthroughs across the public and private sectors.

HARNESSING ELECTROMAGNETIC POWER



NRL'S RESEARCH AND DEVELOPMENT IN ELECTROMAGNETIC WARFARE CONTINUES A PROUD CENTURY-LONG TRADITION THAT CONTINUES TO BE ESSENTIAL TO MAINTAINING AND EXTENDING THE NAVY'S OPERATIONS ACROSS THE GLOBE.

NRL photo

NRL takes a leading role in research and development in support of the Navy's electronic warfare missions. These include electronic warfare support measures, electronic countermeasures, and supporting counter-countermeasures, as well as studies, analyses, and simulations for determining and improving the performance of electronic warfare systems. Altogether, NRL continues to provide a suite of technologies vital to warfighters' protection and strategic edge.

Invention of US Radar

The invention of US radar is one of NRL's signature early accomplishments. While conducting tests of a high-frequency radio in the 1920s, a small team of researchers discovered that the radio signal was disturbed by nearby stationary and moving objects. They were even able to isolate the signal variations by targeting ships on the Potomac River.

While these initial results were very intriguing, other research priorities occupied their work for nearly ten years. The team revisited the phenomenon while working on a later project involving radio guidance for flying and landing aircraft. In the course of that research, they used their earlier discovery to develop a method of detecting and determining the range of those aircraft. By 1936, NRL had invented and patented the first US radar system, a system that reshaped the world we know today. First installed on a major warship in 1938 as the XAF radar aboard the battleship USS New York (BB 34), a modified version of the radar would be deployed on the fleet more widely as the CXAM-1 in time for the beginning of US participation in World War II.

Identification Friend-or-Foe Systems

In 1937, NRL developed the first US radio recognition system for avoiding the destruction of friendly ships, now known as Identification Friend-or-Foe (IFF) system. The IFF provided air-to-surface coded transmissions from an aircraft, received for identification aboard a ship, with transmissions back to the aircraft for verification.

Further work on the IFF system expanded its uses and its efficiency, and the system's utility continues through the present day. Not only does the IFF make an essential contribution to military decision-making, it also greatly enhances the operation of the world's air traffic control system.

Plan-Position Indicator

To provide a polar-coordinate, map-like display of targets, NRL originated the radar Plan-Position Indicator (PPI) in 1939. The PPI is still universally used by military and commercial organizations for the display of radar information for such functions as air and surface detection, navigation, air traffic control, air intercept, and object identification. NRL research and development was essential to both the magnetic (rotating and fixed-coil) and electrostatic deflection types of PPI.

Monopulse Radar

NRL developed the world's first monopulse radar in 1946. Monopulse technology was a significant improvement over existing systems, allowing for angular determinations to be made simultaneously on each received pulse. This breakthrough provided a tenfold improvement in angular accuracy over what was previously attainable.

Monopulse radar was first applied to the Nike-Ajax missile system, the first US continental air defense system. It became the standard radar for missile ranges and was used extensively in a variety of Navy systems, including the guidance system of the Talos missile.

High-Frequency Direction Finding

NRL demonstrated technology that permitted a radical improvement in the performance of high-frequency direction finding networks. By 1957, NRL's innovations enabled the ability to determine the orbit of the Soviet satellite Sputnik I.

The first operational US naval radar, the CXAM-1, was the result of NRL's research efforts during the 1930s and was deployed on a variety of ship types during World War II. NRL photo

In November 1960, the Soviets began short-burst communications. Within weeks, NRL established a project to discover and crack the new communication method. NRL determined that the submarines had switched to short-burst, high-frequency (HF) transmissions, which lasted only tenths of a second compared to the much longer and easier to triangulate Morse transmissions. NRL developed a new recording system, the AN/FRA-44, which was able to track the high-frequency transmissions.

The AN/FRA-44, based on the work of Project Boresight, was soon able to track nearly all Soviet submarines around the world, and played a key role in the outcome of the 1962 Cuban Missile Crisis.

Over-the-Horizon Radar

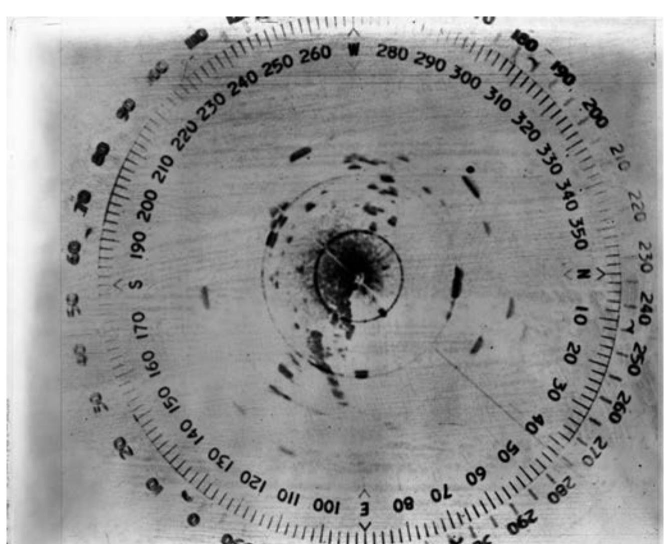
By 1955, NRL was already operating a low-power, HF radar called MUSIC (Multiple Storage Integration Correlation) which demonstrated Earth backscatter at over-the-horizon (OTH) distances and echoes from line-of-sight targets. This system also observed nuclear explosions at long range, as well as the launch of rockets.

In 1961, based on the success with MUSIC, a high-power, high-antenna-gain OTH radar known as MADRE (Magnetic Drum Radar Equipment) was installed at the NRL Chesapeake Bay field site. It was able to detect and track aircraft as they traveled across the Atlantic Ocean. With the NRL MADRE experimental radar, nearly all the fundamental capabilities of HF OTH radar were discovered and demonstrated: aircraft detection and tracking, ship detection, missile launch detection, nuclear test location, sea state determination, storm tracking, and vectoring aircraft to intercept. These capabilities remain crucial to warfighting as well as civilian ventures.

High-Resolution Radar

In 1960, NRL embarked on a major effort to develop X-band high-range resolution radar technology for periscope detection, and to detect the surface effects generated by a submerged submarine. A ten-nanosecond-pulse, rapid-scan, X-band radar was designed, built, and first installed aboard USS Maloy (EDE 791).

Periscope detection and tracking capability were found to be superior to that of conventional search radars because of the ability to distinguish periscope-radar return from that of the sea background. In 1965, the Bureau of Aeronautics (now Naval Air Systems Command) initiated procurement of an antisubmarine radar for new S-3 carrier-based aircraft that would employ the technology developed by NRL.



NRL originated the radar Plan-Position Indicator (PPI) in 1939. The PPI is still universally used by military and commercial organizations for the display of radar information. NRL photo

Super Rapid-Blooming Off-board Chaff

NRL developed the first widespread decoy system applied to all major Navy surface combatants. The MK-36 and the MK-182 cartridge were operationally evaluated in 1977.

Because of the success of this system, a follow-on international program was established to provide the continual product improvements that result from ongoing innovation. This international program led to the development of the MK-214 and MK-216 cartridges, which entered the fleet in 1987 and 1988, respectively, and are in current use.

The Super Rapid Bloom Offboard Countermeasures (Super RBOC) Chaff and Decoy Launching System and its family of decoys has been used by the Navy and its allies for many years.

Specific Emitter Identification

Specific Emitter Identification (SEI), developed by NRL in 1977, allows electronics intelligence signal collection platforms to uniquely identify a radar transmitter with such high accuracy as to make it possible to assign a "fingerprint" to that particular signal. Using SEI techniques, systems with a radar transmitter can be cataloged and tracked, and the data interchange ability between SEI systems allows a signal to be collected by one system and then "handed off" to another system for tracking.

SEI can be used to covertly track a contraband transport whose signal of interest can be collected by an aircraft and then transmitted electronically to a ship for subsequent tracking. The National Security Agency recognized NRL's concept and equipment in 1993 as the SEI national standard after a competition among industry and other service laboratories. SEI systems are currently deployed on ships, aircraft, submarines, and ground sites throughout the armed services.

Inverse Synthetic Aperture Radar

The NRL-developed Inverse Synthetic Aperture Radar (ISAR) is a coherent imaging technique for classifying ships at sea. ISAR processes the radar echoes in extremely fine range-resolution cells, resolving the Doppler frequency shift between scatters caused by the ship's angular change (roll, pitch, and yaw) during an observation interval.

ISAR also produces a PPI map, similar to an air traffic control screen, of the ocean in which detected ships appear as bright blips. When a radar operator designates a blip with a cursor, the radar antenna "searchlights" the ship position, and a continuous series ISAR ship images appear on the screen.

In the 1950s, NRL initiated "Project Boresight," a program that sought to make radical improvements in high-frequency, direction-finding networks. The AN/FRD-10 antenna, shown here at Naval Radio Station Pearl Harbor, was originally developed to pick up new advanced Soviet communications. Library of Congress photo

As an ocean surveillance tool, the Navy uses ISAR for providing ship classification and the targeting for long-range missiles. The APS-147, which also incorporates ISAR in its operations, is now installed in SH-60R helicopters.

Infrared Threat Warning

In 2001, NRL performed ground-breaking research and development on a passive antiaircraft missile warning system intended to detect infrared (IR) radiation from missile plumes fired at aircraft to enable the effective use of countermeasures.

The system evolved from initial concept analyses and proceeded through sensor development, measurements to verify the concept, and demonstration of a system suitable for engineering development. Implementation of the concept required use of high-sensitivity IR focal plane arrays. This NRL innovation continues to protect aviators to this day.

Anti-Ship Missile Defense Radar

NRL scientists have developed and tested shipboard radars that can detect and track low–radar-cross-section air and surface targets in heavy clutter environments. The concept was rapidly developed, demonstrated, and transitioned to production at an affordable cost. The production contract for what became the AN/SPQ-9B radar was awarded in 1994.

The AN/SPQ-9B scans out to the horizon and performs simultaneous and automatic air and surface target detection and tracking of low-flying antiship cruise missiles, surface threats, low and slow flying aircraft, unmanned aerial vehicles, and helicopters. The AN/SPQ-9B continues to be a critical tool for warfighters and homeland defenders.

Radar Arrays for Communication

The evolution of Navy radar from analog phased arrays to increasingly digital architectures has enabled multiple, simultaneous beams for reception while transmission remains largely limited to a single function at a time. This asymmetry is increasingly untenable, as radars evolve into distributed systems reliant on robust communications links often provided by the radars themselves.

The key obstacle is the saturated amplifiers used on transmit, as their nonlinearity precludes conventional linear beamforming. NRL is currently conducting fundamental research into array-waveform designs which are compatible with existing and future radar transmitters, setting the stage for future applied research.

Ultra-wide Bandgap Semiconductors

Ultra-wide bandgap materials have bandgaps greater than those of gallium nitride semiconductors, giving them the ability to handle higher voltages while making the device smaller, faster, and more efficient. Several of the ultrawide bandgap materials also enable higher power operation with less heating.

NRL's work on these materials portends an anticipated five-to-eight-fold improvement in radio frequency power density relative to current semiconductors. This advancement in materials is quickly becoming a benchmark.

This research means that systems can operate at higher range, perform better at close range, and use less power. NRL will continue its legacy of pioneering innovation across the spectrum of electromagnetic warfare.

NRL photo

CHEAPER, BETTER, STRONGER

NRL HAS PIONEERED MAJOR DEVELOPMENTS THAT HAVE ENHANCED THE AFFORDABILITY AND SUSTAINABILITY OF MILITARY SYSTEMS ACROSS ALL ARENAS.

NRL was responsible for the creation of advanced structural-testing solutions that remain state of the art, as well as numerous materials-technologies that have revolutionized everything from the smallest microtransistor to the decks of the largest American ships. Many of these developments have also been passed on to private industry and provided great benefits to civilian life and national infrastructure. The years ahead will see the development of more ground-breaking technologies in robotics and artificial intelligence.

Gamma-Ray Radiography

In the 1920s, NRL developed gamma-ray radiography, which was an important contribution to the nondestructive testing of metal castings and welds for shipbuilding. Using radium as a source of gamma rays, and with exposure times measured in hours, NRL researchers were able to image and measure internal cracks in bad castings and welds before parts failed, preventing their installation into new vessels and improving the cost, safety, and maintenance requirements.

NRL's research established gamma-ray radiography as a testing technique for the nation's military and industrial base. It also improved the production of high-quality steel for armor, ship frames, and fittings. In the years since, gamma-ray radiography has found use in numerous industrial applications, such as inspections of the internal structure and integrity of welds on pipelines and pressure vessels.

Principles of Fracture Mechanics

Fracture mechanics is a field that recognizes that all structures are manufactured with or will ultimately contain flaws that govern the eventual failure of the structure. The study of the stresses caused by flaws, and the material's resistance to failure from them, forms the basis for the field of fracture mechanics. These new design principles increased the reliability of structures, because of improved design capability, and an improved predictive capability of in-service damage.

NRL's George R. Irwin is recognized as the pioneer of modern fracture mechanics. As a consequence of his ground-breaking work in the mid 20th century, fracture mechanics is taught in many undergraduate and graduate curricula and remains an active field today. The principles of this scientific field have been applied throughout the military and the world for the design of any structures where sudden catastrophic failure would cause loss of life or other serious consequences. Examples include nuclear reactor pressure vessels, submarines, aircraft, missiles, and tanks for storage of toxic or flammable materials.

Fracture Test Technology

In addition to studying the basic science of fracture, NRL researchers also established methods for prevention of fracture based on experimental methods. In the 1940s, NRL solved the mystery of brittle fractures of World War II Liberty ships, in which entire ships sometimes fractured, even in calm water and dockside, establishing techniques that are still relevant in the age of high-performance ships, aircraft, and missiles.

NRL is still recognized as a leading international center for the development of structural integrity technology. The Navy relies on NRL's expertise to assure the structural integrity of aircraft, ships, and submarines, and in doing so, to safeguard their crewmembers.

Synthetic Lubricants

Soon after the introduction of gas turbine-powered jet aircraft in World War II, newer and better lubricants were required to take advantage of the potential capabilities of these engines. Leveraging NRL's previous success in developing synthetic lubricants for instrument bearings, in 1947 the Navy Bureau of Aeronautics requested that NRL undertake the development of lubricating oils for turbojets and gas turbines.

In response, NRL developed the first hydrocarbon ester fluids as lubricants that would perform acceptably at the high-bearing operating temperatures in jet engines. As turbine engine power requirements and operational temperatures increased, NRL developed lubricants and lubricant additives to meet these more demanding conditions. Essentially, all turbine engines now used by military and civilian aircraft are lubricated with ester oils based on early research and development conducted at NRL.

High-Temperature Nonskid Decking

With the advent of vertical-landing-and-takeoff aircraft such as the F-35 Lightning II, amphibious landings were anticipated to result in on-deck temperatures high enough to incinerate legacy organic nonskid materials. This was observed during testing on USS Wasp (LHD 1) in 2011. In response, NRL developed Thermal Spray Nonskid (TSN), which is an inorganic, nonskid decking that is robotically applied using arc-wire thermal spray processes of commercially available hybrid aluminum/ceramic feedstock.

This system was used to solve a flight deck readiness issue caused by operations of MV-22 and AV-8B aircraft on amphibious ships. The issue was elevated because of several AV-8B engine casualties and curtailed flight operations resulting from foreign-object debris caused by failing nonskid coatings. TSN was shown to be a viable solution to the flight deck problem. In 2014, at the direction of Fleet Forces Command, NRL led the transition of this technology to the amphibious ship fleet.

Fluorinated Network Polymers

Polyurethane coatings were introduced in the 1960s, as a material to line fuel tanks used for long-term storage of aviation, marine, and vehicle fuels. To improve the polyurethane coatings, NRL developed tank-linings consisting of a fluorinated polyurethane filled with Teflon powder. The material is both hydrophobic and oleophobic and impermeable to water, gases, hydrocarbons, and other corrosive agents.

The estimated total life-cycle savings for using NRL's fluorinated urethane coatings in place of conventional urethane coatings was \$11.4 million, and more than \$33 million in place of epoxy coatings, based on 18 fuel tanks coated by 1998.

NRL's fluorinated polymer coating is still an effective lining for the fuel tanks at naval air stations and support facilities. It also saves a significant amount of money over the life of the tanks. Its properties provide other uses as well, such as improved water-shedding on the BRA-22 radomes of all Los Angeles-class submarines.

Improved Boilerwater Treatment

Naval high-pressure steam propulsion boilers are subject to the damaging effects of corrosion and scale formation on the watersides if a proper boilerwater treatment is not applied. Traditional methods of cleaning required ships' boilers to be out-of-service and increased crew workload and maintenance time.

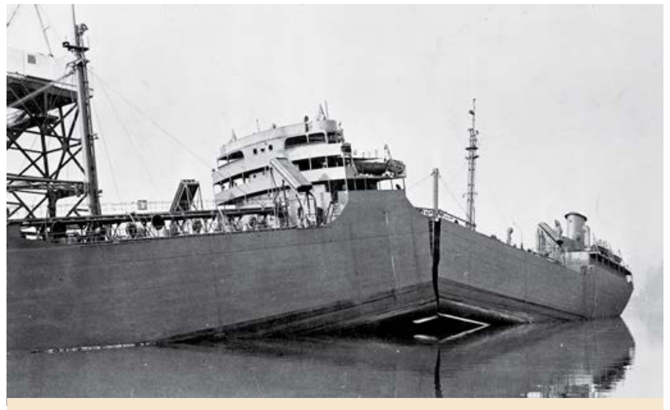
In the 1960s, NRL started investigations into new water treatments to clean in-situ high-pressure boilers. This led to a final treatment that included the addition of hydrazine to stabilize the ethylenediaminetetraacetate solutions upon their addition to the boilers. After excellent results from four trial ships, the chief engineer of Naval Sea Systems Command directed the implementation of this new treatment, which extended the normal, 1,800 hours of operation between cleanings to 15,000-20,000 operation hours.

NRL's research was instrumental to keeping Navy ship boilers in service for much longer periods and in reducing the costs and crew workloads associated with frequent cleanings.

Magnetic Materials and Semiconductor Technology

In the 1970s, NRL recognized that developments in semiconductor materials technology could be leveraged to fabricate new magnetic materials in thin-film form. NRL's work was a key technology development that enabled the demonstration of the giant magnetoresistance (GMR) effect by laboratories in France and Germany using iron/chromium (Fe/Cr) multilayers epitaxially grown on gallium arsenide (GaAs). The 2007 Nobel Prize in Physics was awarded to Albert Fert and Peter Grünberg for the discovery of GMR.

The use of magnetic metal films on semiconductors for sensors is now widespread. The largest use is in read heads for computer hard disks. They are under development for mechanical motion sensors by the automotive and machine tool industry, as well as by the military for fuses and perimeter defense. The largest impact may be for nonvolatile magnetic memory in computers, which is under



In the 1940s, NRL solved the mystery of brittle fractures of World War II Liberty ships, in which entire ships sometimes fractured, establishing techniques that are still relevant in the age of high-performance ships, aircraft, and missiles.NRL photo development at several corporations within the United States as well as abroad in Japan, Germany, France, and the Netherlands. The domestic industrial efforts are supported by the Defense Advanced Research Projects Agency.

In the commercial arena, magnetic metal films on semiconductors, exploited for the giant magnetoresistance effect, was by 1998 generating $10 billion in sales for sensors in read heads, and the introduction of magnetic computer memory was projected to impact a market measured at $100 billion annually. For military applications, this technology promised far better performance of satellites, missile guidance, and aircraft navigation.

Semi-Insulating Gallium Arsenide Crystals

In the 1970s, NRL invented and developed a liquid-encapsulated Czochralski (LEC) method of compounding and growing high-purity, single crystals of GaAs that were semi-insulating in nature without the need for doping. Wafers made from these crystals are critical to produce high-performance microwave and millimeter-wave devices, integrated circuits, microcircuits, and transistors.

Soon after the introduction of gas turbine-powered jet aircraft in World War II, newer and better lubricants were required to take advantage of the potential capabilities of these engines. Since then, NRL has developed a wide variety of lubricating oils for turbojets and gas turbines. NRL photo

NRL's technology was adopted by major industrial firms such as Rockwell International, Westinghouse, Texas Instruments, and Hughes Research. Military systems using these technologies include all forms of military radar and electronic warfare, communications, satellite, and weapon systems such as HARM, AIM-54 Phoenix, AIM-9L Sidewinder, and AMRAAM. Commercial uses are ubiquitous and include weather and navigation radar, communication systems including cellular and satellite systems, and wireless LANs.

,

This technology provided savings to the military for the ten-year period from 1979 to 1989 of more than $560 million (in 1986 dollars). This is all the more impressive given that the original investment in NRL's research was $528,000.

Ion-Implantation Metallurgy

In the late 1970s, NRL researchers devised a surface-modification technique to develop new metal alloys with enhanced properties and operating lifetimes by accelerating ions (electrified atoms) and implanting them into the surface of ordinary materials. This process, known as ion-implantation metallurgy, has found great application in improving the performance, increasing the corrosion resistance, and reducing the friction and wear of critical components such as ball bearings.

Refurbishment and replacement of bearings, which in the 1980s cost up to $3,000 each, was a significant maintenance expense, but NRL's research in ion-implantation offered an answer to this problem.

Ion-implantation improved the service lives and shelf lives of expensive bearings and other components from 100 to 1000 percent where the downtime time required for their replacement is high. Results also showed that the bearings could be implanted for between $70 and $170 per bearing, and that this cost was more than paid for by the average increase in the bearing service life of more than double.

The early NRL work established the standard for ion-implantation metallurgy. NRL's technology led to advances in corrosion protection of ball bearings on naval aircraft, and the process also benefitted the Army and found application in commercial processes.

Molecular Structure Analysis

NRL has produced two Nobel Laureates—Dr. Jerome Karle and Dr. Herbert A. Hauptman—who each received the Nobel Prize for Chemistry in 1985 for devising direct methods employing X-ray diffraction analysis in the determination of crystal structures.

Dr. Isabella Karle made a major contribution to the development of analytical techniques of broad applicability to all types of crystals, whether they had centers of symmetry or not. It was a considerable step to bridging the gap between theory and practical application. Dr. Isabella Karle was honored with the National Medal of Science.

X-ray diffraction analysis involves the determination of the arrangement of atoms in crystals from which the molecular formula is derived directly. Determination of the molecular structure is important in that once the structural arrangement is understood, the substance can then be synthesized to produce useful products. This research occupies a unique position in science because the information it provides is used continuously in other fields. In fact, many phenomena in the physical, chemical, metallurgical, geological, and biological sciences are interpretable in terms of the arrangements of atoms.

In 2009, President Obama congratulated Drs. Isabella and Jerome Karle on their combined 127 years of federal service in scientific research:

"The reputation of the Naval Research Laboratory as one of the preeminent research facilities in the world was certainly enhanced by your work even as its strong creative environment nurtured your efforts. That relationship testifies to the idea that the pursuit of fundamental knowledge lies at the heart of technological progress, national security, and international leadership, and it exemplifies the importance of the Defense Department's cadre of career civilian scientists."

Quantitative X-Ray Fluorescence Analysis

NRL researchers have introduced many of the developments which have made X-ray fluorescence analysis (XRF) the quantitative method that it is today. NRL brought XRF to maturity by pioneering the use of new instruments such as the electron microprobe, curved crystal spectrographs, and multichannel energy analyzers, and by devising novel analytical methods and computer codes that implement them.

It has been estimated that by the 1990s more than 1,000 laboratories worldwide had used the NRL software or similar programs employing the fundamental-parameter approach developed at NRL. Virtually every X-ray chemical analysis system produced today incorporates one or more of NRL's seminal advances in instrumentation and analysis. NRL's research in XRF also resulted in industrial applications in mining, manufacturing, and metals recycling.

Low Solar Absorbance Ship Paint

NRL developed low solar absorbance (LSA) paint in order to reduce solar heating on Navy ships. The paint was tested in 1995, demonstrating that LSA not only reduced ship-surface temperatures and the load on air conditioning systems, but it also decreased the ship's infrared signature. Following successful application on USS Dextrous (MCM 13), LSA paint was transitioned into the fleet, and all Navy ships were painted with the NRL-designed paint.

LSA paint reduced solar heating on Navy ships, leading to lower air conditioning and maintenance costs and greater crew comfort. The paint has reduced the susceptibility

In the 1970s, NRL developed a method for compounding and growing high-purity, single crystals of gallium arsenide. Wafers made from these crystals are critical to produce high-performance microwave and millimeter-wave devices, integrated circuits, microcircuits, and transistors. NRL photo

of all coated Navy ships to hostile infrared sensors and to infrared-guided munitions. The per-gallon cost of the LSA paint is virtually identical to the Federal Standard Haze Gray paint it replaced, resulting in a cost-effective infrared stealth technology for the Navy. For many years it was the standard Navy paint system and the concepts of pigmenting paints for LSA properties are still in use today in new generations of paint systems.

Rapid Cure Corrosion Control Coatings

NRL pioneered, developed, and commercialized durable, rapid-cure coatings designed for harsh environments. Such coating systems reduced a three-coat painting process to a single-coat process and offer a near instant "walk-on time" and rapid return to service, typically in minutes, not hours or days as with other systems. Superior chemical resistance also makes it suitable for the interior and exterior of shipboard tanks for fresh water, seawater, fuel, and waste. The coatings provide a lower environmental impact and longer times between repainting: typical recoat times for legacy materials was three to five years; these new solvent-free coating systems are expected to have a 20-year service life. After more than 70 successful demonstrations across 18 platforms, the rapid-cure coatings were mandated for use in all seawater ballast tanks.

According to NAVSEA, the potential fleet-wide cost savings over the coatings' expected 20-year lifecycle is $1.8 billion. In 2012, the NRL team was recognized with the Office of Naval Research Prize for Affordability for their development of rapid-cure, single-coat tank coatings. This technology continues to make a significant contribution toward reducing the total ownership costs associated with the corrosion control of Navy ships and submarines.

Patrick Mahan, from the US Naval Research Laboratory, conducts drills aboard USS *New York* (LPD 21) in August 2023. This year, the Navy's corporate laboratory is commemorating 100 years of service and achievement in the development of science and technology for the sea services and the nation. Photo by MCSN William Bennett IV

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

Future Force
Office of Naval Research
875 N. Randolph Street, Suite 1425
Arlington, VA 22203-1995

Email: futureforce@navy.mil
Phone: (703) 696-5031
Web: http://futureforce.navylive.dodlive.mil
Facebook: http://www.facebook.com/navalfutureforce