U.S. NAVAL RESEARCH LABORATORY

The Naval Research Laboratory and Our Mission Over a Century: 100 Science and Engineering Contributions to Sea Power and National Security

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

1923–2023

This is a momentous milestone. The centennial of the Naval Research Laboratory (NRL) invites us to look back and reflect on the Laboratory's impressive record for creating significant scientific and engineering advances that support the U.S. Navy and national security. At the same time, this event inspires us to look forward, with renewed commitment, to a critical defense mission that can never rest.

This publication commemorates NRL's century of service, which began on July 2, 1923, by featuring 100 achievements that exemplify the Laboratory's extraordinary impact on American sea power and national security. Many of its contributions were made during times of great peril to our nation, the free world, and democracy. NRL has changed the way the U.S. 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 with the first U.S. radar, the world's first intelligence satellite, and the first operational satellite of the Global Positioning System.

NRL has helped create — in league with its government, university, and industry partners — the most formidable naval fighting force on earth, which, in turn, shaped America's role in the world. Reflection on our accomplishments should encourage and prepare us for the exertions and sacrifices required to meet tomorrow's inevitable challenges.

The unclassified accomplishments presented in this book are only representative of thousands, many of them still classified, that NRL has produced since opening its gates. It should be noted that the more recent achievements may not have yet reached full fruition in terms of applications and impact. Even so, the 100 narratives that follow by themselves confirm that NRL exerts a broad and powerful influence on our Navy and our republic through the work of dedicated government scientists, engineers, and support personnel who serve the nation's interests.

Dr. Bruce G. Danly
Director of Research
U.S. Naval Research Laboratory

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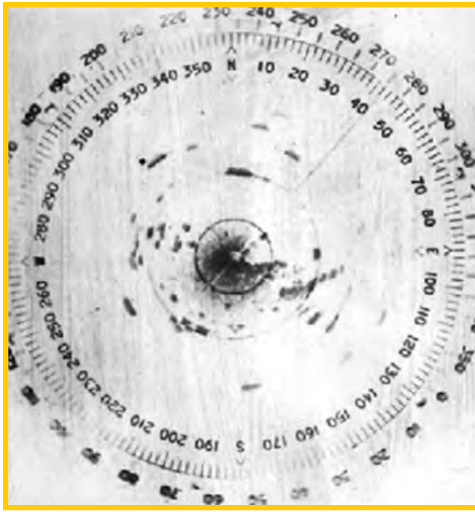
INVENTION OF U.S. RADAR

Prior to the development of radar, Navy ships could track other ships or aircraft only by using optical techniques, sound ranging, or primitive radio direction finding. New methods of detection and ranging were necessary. In 1922, while working on radio direction finders for aircraft, A.H. Taylor and L.C. Young noted a distortion of "phase shift" in radio signals reflected from a steamer on the Potomac River. In short, NRL had detected a moving ship by radio waves and, as a result, had discovered the radar principle. Eight years after the initial discovery of the radar principle, NRL scientists observed that reflections of radio waves from an airplane also could be detected.

From 1930 to 1940, NRL explored the use of radio for detection and ranging. In 1933, the use of a pulse technique to detect aircraft and ships was proposed by Young. R.M. Page made major advances over the next few years in the area of transmitters and receivers, eventually developing the highly important "duplexer" in 1936. The duplexer permitted the use of the same antenna for both transmitting and receiving. The pulse technique combined with the duplexer did away with the separate receiving and transmitting antennas that most of the other early radar developers employed. Page and Young received the patents for the duplexer, an invention that dramatically changed the nature of radar in the U.S. and abroad.

IMPACT: NRL invented, developed, and installed the first operational U.S. radar, the XAF, on the battleship USS *New York* in 1939. It was rapidly transferred to industry for production. By the time of the attack on Pearl Harbor, 20 radar units were in operation. Radar of this type contributed to the victories of the Coral Sea, Midway, and Guadalcanal. Among the lessons learned at Coral Sea was that every carrier should be equipped with two long-range radars. The invention of radar and the developments that flowed from it (e.g., monopulse radar and over-the-horizon radar) are among the foundations of modern military power. And as a sensor for navigation and surveillance, radar plays a major role in the operation of civilian transportation systems, weather forecasting, astronomy, and automation, among other uses.

PLAN-POSITION INDICATOR



When NRL demonstrated the first U.S. radar, the XAF, during fleet exercises in 1939, it was observed that the radar's use could be facilitated by a display presenting a polar-coordinate map. Such a map would indicate the range and bearing of all objects "visible" to the radar. To provide a polar-coordinate map-like display of targets, between 1939 and 1940, NRL originated the radar plan position indicator (PPI) — the well-known radar scope with the round face and the sweeping hand. It was developed independently in England and in the U.S. when neither country knew of the work in the other country.

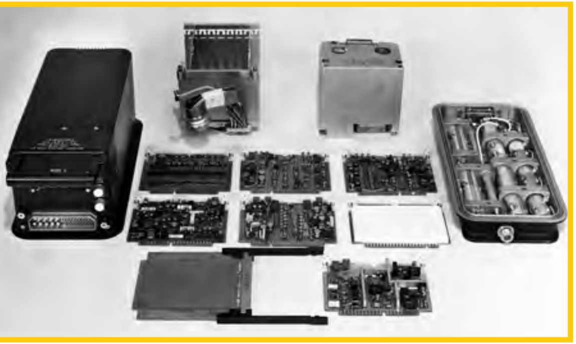
The PPI was an efficient means of display for many reasons, not least because many radar antennae were large, slow-turning structures and the phosphorescent flashes of radar reflections were quickly there and gone again. As NRL's R.M. Page wrote, "it was not possible for the eye or the mind to retain or remember all the flashes in their correct positions for one complete rotation." As is necessary for any such sensor readout, the data needed to be usable by a human, so NRL deployed a colored filter with a mix of phosphor types on the PPI screen. With this system, the radar blips persisted from sweep to sweep of the antenna.

NRL's PPI was first utilized in the experimental model of the SG radar, which was installed and demonstrated on the destroyer USS *Semmes* in April 1941. The Model SG (developed by The Radiation Lab and Raytheon) became the fleet's first radar to be equipped with the NRL-developed PPI display. Nearly 1,000 Model SG radars were produced during World War II and many remained in service for nearly two decades. The PPI would become particularly useful when "combat information centers" were established aboard command vessels in the fleet.

IMPACT: The PPI is now universally used by military and commercial interests of the world for the display of radar information for such functions as air and surface detection, navigation, aircraft traffic control, air interception, and object identification.

IDENTIFICATION FRIEND-OR-FOE SYSTEMS

NRL developed the first U.S. radio recognition identification friend-or-foe (IFF) system, the Model XAE, in 1937. This system provided coded transmissions from aircraft, which were received for identification aboard ship and transmitted back to aircraft for verification. In 1939, NRL devised the first U.S. IFF system in which radar pulses received by a target ship or aircraft were repeated back to the radar and displayed as a pulse associated with the echo pulse on the scope. This capability became possible after NRL's R.M. Page developed the first U.S. pulse transponder, which was basic to pulse IFF systems and pulse beacon systems.



In 1940, NRL developed the Mark IV IFF system, the first to provide a means for target isolation in azimuth as well as range. The Mark IV was used operationally in the Pacific theater. In 1942, NRL was designated leader of the U.S.-U.K.-Canadian scientific effort to develop the next-generation Mark V IFF. The Mark V incorporated many important NRL features, greatly reducing the time needed to identify a target, increasing transponder range, and improving isolation of targets in azimuth. After the war, NRL adapted the Mark V to track jet aircraft. This became known as the Mark X, which was essential because it reduced fratricide when using beyond-visual-range weapons.

By 1958, the Federal Aviation Administration established the Air Traffic Control Radar Beacon System, essentially the civil version of the Mark X. The International Civil Air Organization later adopted the system, making the Mark X the basis of the world's air traffic control system. NRL's work, as well as the work of institutions such as the Air Force Cambridge Lab, led to the Mark XII IFF system in 1960. This was the first system to use cryptographic techniques to prevent deception in which an enemy appears as a friend by using a captured transponder (the device giving the "yes" answer to interrogations).

IMPACT: NRL's successive IFF systems met urgent operational requirements for the U.S. and the Allies' armed forces to discriminate friendly units from enemy units. In subsequent developments, the Mark X impacted U.S. and allied armed forces, as well as national and world civil airways, and the cryptographic Mark XII essentially nullified the threat of deception by an enemy using captured IFF transponders.

MONOPULSE RADAR

To overcome the angle-measurement limitations of existing radars, NRL developed the first monopulse radar in 1943. As the name implies, the monopulse technique makes angle measurements on each received pulse. This new type of radar provided a tenfold improvement in angular accuracy over prior systems. Ideal for tracking maneuvering targets, monopulse radar is now the basis for all modern tracking and missile control radars. While the concept for monopulse radar was also independently developed elsewhere, the Laboratory's R.M. Page holds the U.S. patent on this technique.

The monopulse technique was first applied to the Nike-Ajax missile system, which was the nation's continental air defense system. The radar of this system was patterned after NRL's experimental model. NRL's work eventually led to the AN/FPS-16, developed jointly by NRL and RCA, which was the first radar designed to support test missile tracking. As part of this work, NRL researchers achieved another first, feeding AN/FPS-16 tracking data directly into an IBM 709 computer, which, in turn, drove plotting boards in Central Control. In this manner, they tracked the launchings of the first U.S. space satellites, Explorer I and Vanguard I, at Cape Canaveral in 1958.

After additional improvements to provide a more compact and efficient monopulse antenna feed and lobe comparison waveguide circuitry, monopulse tracking radar became the generally accepted tracking radar system for military and civilian agencies, such as the National Aeronautics and Space Administration (NASA) and the Federal Aviation Administration (FAA), and remains in wide use today.

IMPACT: The invention of monopulse (simultaneous lobing) tracking radar was a breakthrough in precision target tracking. Monopulse radar performance is critical to gunfire control, missile guidance, missile-range precision launching, range safety, space vehicle tracking, FAA civil aircraft landing systems, Navy aircraft carrier landing systems, and target recognition.

FIRST AMERICAN AIRBORNE RADAR

Prior to the entry of the U.S. into World War II and in anticipation of having to contend with the German submarine menace, NRL developed the U.S.'s first operational airborne radar (the Model ASE) followed by what became the first widely used U.S. airborne radar (the Model ASB). For the ASE, NRL modified the UK Model ASV Mark II radar, replacing its cumbersome antenna system with an NRL design, greatly increasing potential airspeed. Hundreds of NRL ASE radars were used as standard equipment on PBY flying boats, yet were ill-suited for the torpedo bomber TBF Avengers.

By the time the ASE was adopted for use, NRL already had its own 60-cm air-surface radar, the ASB, in development. When completed, the Model ASB became the first radar used in carrier-based aircraft. It proved far superior to the ASE, in part because it featured a higher frequency and an even smaller, lighter antenna system.

The ASB became known as the radar that fought the war from the air in the Pacific. It was the first operational U.S. airborne radar widely used for bombing, detection of ships and surfaced submarines, and airborne interception. As the first radar to be used in carrier-based aircraft, the ASB was employed in attacking and destroying Japanese ship convoys in the Pacific. It was also very effective against submarines because it tremendously widened the area that could be covered by patrol planes.

IMPACT: The ASB radar saw extensive use during World War II, not just by the U.S. Navy and the U.S. Army Air Corps, but also by the British military. It was installed almost universally in U.S. naval aircraft and became known as the "work-horse of naval aviation." Between 1942 and 1944, more than 26,000 units were procured, the largest procurement of any radar model during the war. Experience with this type of radar led to NRL's involvement in the UHF E2 Airborne Early Warning Radar, microwave interception radars, and anti-submarine warfare periscope detection radars.

RADAR ABSORBING MATERIALS AND ANECHOIC CHAMBERS

Since the end of World War II, NRL has pioneered the development and production capabilities for thin, magnetic, radar-absorbing materials (RAM), thicker, nonmagnetic RAM, and designs for radar anechoic chambers. In 1945, the "NRL Arch" apparatus was constructed to provide a means for measuring angular-dependent performance of broadband RAM. The name "NRL Arch" is still used, and the apparatus is accepted worldwide by RAM manufacturers and stealth technology contractors. In 1953, NRL developed a broadband, nonmagnetic material called "DARKFLEX," the precursor to materials used in today's radar anechoic chambers. NRL initiated a pilot production plant, then transferred large-scale production to Sponge Rubber Products Company. Also in 1953, NRL assembled the first effective radar anechoic chamber. The design and elements of it are contained in most chambers today.

The fundamental mechanisms of absorption by magnetic ferrites and alloys were extensively investigated at NRL by a group headed by G. Rado. The understanding of these fundamental mechanisms (magnetic moment rotation, domain wall displacement, and spin-waves) allowed the development of broad-bandwidth-frequency coverage, thin, magnetic RAM. This led to the NRL project "NEW-BOY," initiated in 1976. Thin RAM materials from this project were extensively used by the Joint Cruise Missile Program Office and the other services as prototype stealth treatments for missile-like drones, aircraft, and ships.

IMPACT: After more than seven decades, NRL continues to be a resource for RAM innovation, prototype production, and measurement tools/facilities. In fact, NRL developed, produced, and in several instances installed materials on Navy/DoD platforms from the end of World War II through Operation Desert Storm. Much of NRL's work preceded efforts on "stealth" technology and significantly impacted it in the areas of submarines, missiles, aircraft, ships, and land vehicles.

OVER-THE-HORIZON RADAR

During the late 1940s, NRL foresaw the need for detecting moving targets, including aircraft and missiles, at distances and altitudes below the visual horizon. The coverage of microwave radar, as developed during World War II, is limited by the curvature of the Earth. In 1950, while using the pioneering propagation work it performed in 1926 (radio "skip distance" effect theory, see page 28), NRL began to investigate the use of radar operating in the high-frequency (HF, or shortwave) portion of the radio spectrum to extend the range beyond the horizon. This is achieved by the refraction (bending) of radar waves when traveling through the ionosphere, which is located high above the Earth's surface. Using the ionosphere to bend the radar energy back to the Earth's surface can extend the range of a radar out to 2,000 nautical miles.

By 1955, NRL was operating a HF pulse doppler radar called MUSIC (Multiple Storage Integration Correlation). MUSIC was eventually able to detect missile launchings at ranges up to 600 nautical miles and atomic explosions up to 1,700 nautical miles. With the use of a bank of Reed filters, it could display multiple aircraft targets.

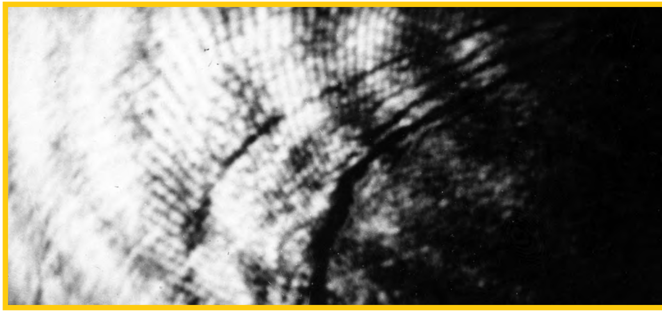
In 1961, based on the success with MUSIC, a high-power, large-antenna OTH radar known as MADRE (Magnetic Drum Radar Equipment) was installed at the NRL Chesapeake Bay field site. It was able to detect and track aircraft as they traveled across the Atlantic Ocean. With the NRL MADRE experimental radar, 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 interceptor aircraft.

IMPACT: NRL's development of OTH radar solved a critical military requirement where the horizon limit of conventional radar was overcome, giving an order-of-magnitude-or-more increase in useful range. This technology provided the technology base that led to the Air Force's AN/FPS-118 radar for continental air defense and the Navy's AN/TPS-71 Relocatable Over-the-Horizon Radar. It also influenced HF radar development in other countries of the world. HF OTH radar remains the most cost-effective wide-area sensor available, and as a result, is enjoying a renaissance enabled by signal-processing advances.

HIGH-RESOLUTION RADAR

High-resolution radar is important in many areas of radar. It allows the recognition of targets and the exclusion of unwanted clutter echoes so that small stationary or slowly moving targets can be detected in heavy clutter. The need for high range resolution to detect periscopes was recognized in the late 1940s.

NRL began to explore high-resolution radar for periscope detection and other applications in the mid-1950s. The first high-resolution pulse-compression radars were being developed at that time, thereby demonstrating that the energy of a long pulse could be obtained along with the resolution of a short pulse. Although not alone in this area, NRL was active in advancing the art of pulse compression. Other key contributions were made by MIT Lincoln Laboratory and Bell Labs.



In 1960, NRL embarked on a major effort to demonstrate X-band high-range-resolution radar technology for periscope detection and the detection of surface effects generated by a submerged submarine. This was called Project Cutwater. NRL successfully demonstrated both surface and airborne radar for the detection of submarines. In 1965, the Naval Air Systems Command (then the Bureau of Aeronautics) initiated procurement of an anti-submarine warfare (ASW) radar for new S-3 carrier-based aircraft that would employ the technology developed by NRL. Texas Instruments was awarded the contract for the radar that became the AN/APS-116.

IMPACT: NRL's work in high-resolution radar resulted in ASW radars for the U.S. Navy's S-3 and P-3 aircraft. These high-resolution radars were the only operational U.S. radars for submarine detection for more than 30 years and derivative systems remain in service to this day. By developing the means to detect enemy submarines, the Laboratory met a critical national security need.

HIGH-FREQUENCY DIRECTION FINDING

During the 1950s and 1960s, NRL demonstrated technology that permitted a radical improvement in the performance of high-frequency direction-finding (HFDF) networks and oversaw the deployment of this technology in Project Boresight and Project Bulls Eye.

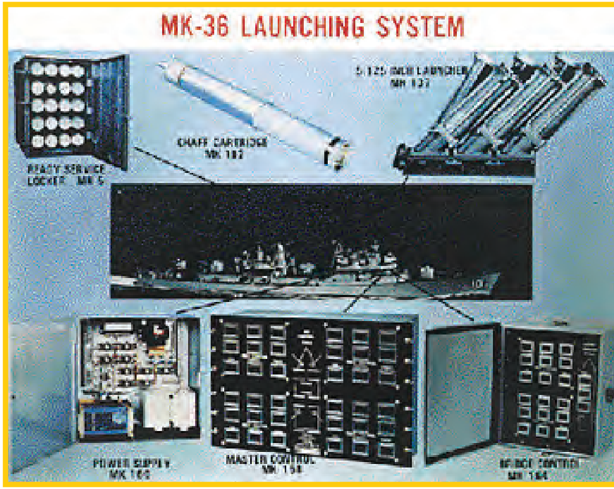
The first of three innovations that underlie NRL's work was retrospective direction finding. Previously, all stations in an HFDF network were required to measure characteristics of the same signal while transmission was still occurring. After-the-fact measurements were needed. Previous attempts were limited by storage bandwidth and recorder instabilities. Recording significant fractions of the HF spectrum and using a digital method for overcoming recorder instabilities enabled retrospective DF. This was the basis of Project Boresight in 1960, which deployed the AN/FLR-7 and the AN/FRA-44 worldwide. Boresight was a classified program initiated when National Security Agency operators, who had been routinely intercepting daily HF signals from Soviet submarines, suddenly noticed no signals. The Soviets were compressing the signals and transmitting them in fast bursts that were too quick to be pinpointed.

The second innovation was the use of circularly disposed wide-aperture direction-finding arrays, which significantly increased HFDF location accuracy and signal-collection capabilities. In the 1950s, NRL had constructed a 400-ft-diameter electronically steerable array and perfected the underlying technology. During Project Bulls Eye, scaled-up versions of this prototype were deployed worldwide by the Navy as the AN/FRD-10. The third innovation was the use of computers for control of the HFDF network and for the prompt triangulation of target locations.

IMPACT: NRL developed the technology to intercept and locate submarine radio burst transmissions that the Soviet Union thought were undetectable. During the Cuban Missile Crisis in October 1962, Project Boresight gave America a significant advantage by providing the capability to track Soviet submarines en route to Cuba. Boresight's crucial contribution to national defense was recognized by the awarding of the Distinguished Civilian Service Award to NRL's R.D. Misner and M.J. Sheets. The more ambitious Project Bulls Eye made HFDF a principal means of global ocean surveillance at the time.

SUPER RAPID-BLOOMING OFFBOARD CHAFF

NRL developed the first widespread decoy system applied to all major Navy surface combatants. The MK-36 and the MK-182 cartridge were successfully operationally evaluated in 1977. Because of the operational 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 successful 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 U.S. Navy and its allies for many years.



IMPACT: Super RBOC and its family of decoys significantly improved the Navy's capability to conduct electronic warfare from its surface combatants. It was a major advancement in the state of the art in its ability to rapidly produce an alternate target for the protection of ships against anti-ship cruise missiles. With the extensive proliferation of the cruise missile threat throughout the world, this solution was especially timely and critical to the survivability of the fleet. It was subsequently replaced by the active decoy Nulka, jointly developed by the U.S. and Australia, which is on virtually all capital ships of the U.S. and Australian navies. Other allied navies still deploy the Super RBOC system.

SPECIFIC EMITTER IDENTIFICATION

Specific Emitter Identification (SEI) provides electronics intelligence (ELINT) signal-collection platforms with the capability to uniquely identify a radar transmitter with such accuracy as to make it possible to assign a "fingerprint" to that particular signal. In using SEI techniques, systems with radar transmitters can be cataloged and tracked, and the data interchangeability between SEI systems allows a signal to be collected by one system and then "handed off" to another system for tracking. For example, 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.

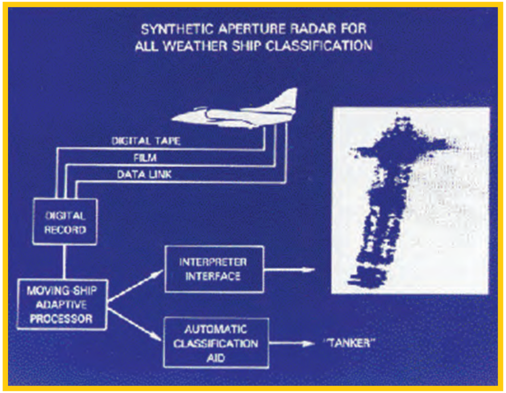
On 14 April 1982, NRL's R. Goodwin was the recipient of the Navy Superior Civilian Service Award. He was cited for "performing and directing the research and development efforts that led to the achievement of an important, new Navy capability in real-time pulsed-emitter characterization."

In June 1993, the National Security Agency (NSA) recognized the superior capability of NRL's SEI concept and equipment after a competition among numerous participants from industry and other service laboratories. The NSA test served as an impartial means for selecting an SEI methodology for use as a national standard. As a result of the test, NSA issued a message (DTG 011440Z, June 1995) that stated in part, "Accordingly, NSA has selected the Naval Research Laboratory processor (L-MISPE) to be the standard for conducting SEI/UMOP collection operations ...."

Since that decision, SEI platforms have been very successful at cataloging and tracking platforms of interest. In one application, a library of over 300,000 specific radar signals was compiled. This library was shared among sites to aid in performing tactical intelligence and surveillance tasks. The platforms for making SEI observations have since proliferated.

IMPACT: SEI identifies radars by their unique characteristics with such accuracy as to "fingerprint" them. In fact, it can distinguish between identical models produced off the same assembly line. With SEI systems deployed on ships, aircraft, submarines, and ground sites, NRL's technology has had significant warfighting impact. It saw combat action in Kosovo and in Operation Iraqi Freedom. Furthermore, Coast Guard vessels, Navy warships, and aircraft have used it to support drug interdiction, to enforce treaties, and to monitor the movement of materials used in weapons of mass destruction.

INVERSE SYNTHETIC APERTURE RADAR



Inverse synthetic aperture radar (ISAR) is a coherent imaging technique for classifying ships at sea. NRL's D.W. Kerr originated the concept for using the ship's irregular motions to provide the angle-aspect change necessary for imaging.

ISAR processes the radar echoes in fine range-resolution cells, resolving the incremental Doppler frequency shift between scatterers caused by the ship's motion (roll, pitch, and yaw) during an observation interval. The Navy uses this as a mode with a scanning surveillance radar. In the scanning mode, the radar produces a plan-position indicator (PPI) map of the ocean in which detected ships appear as bright "blips." When a radar operator designates a blip with a cursor, the radar antenna spotlights the ship position, and a continuous sequence of ISAR ship images appear on the screen.

The AN/APS-116 radar, which was based on earlier NRL developments, was replaced by the AN/APS-137, which has the added capability of performing recognition of ships based on NRL's ISAR technique. The APS-137 was installed in P-3 as well as the S-3 aircraft before the S-3 Viking was retired from Navy service in 2016.

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

IMPACT: ISAR provides the Navy with the important capability to identify targets at considerable ranges. It is included in major operational systems on the Navy's P-8 aircraft, the Navy's MH-60R helicopter, the Coast Guard's C-130 aircraft, and the Navy's Triton long-duration UAV.

INFRARED THREAT WARNING

A passive anti-aircraft missile warning system based on detection of the infrared (IR) radiation from missile plumes was demonstrated by NRL in the 1990s. This device detected heat-seeking missiles fired at aircraft at greater ranges and with lower false-alarm rates than earlier systems based on the ultraviolet signature of the missile launch. The longer-range detection provides earlier warning and hence more time for more effective deployment of countermeasures. Development evolved from initial concept analyses and proceeded through sensor development, measurements to verify the concept, and multiple live-fire demonstrations to reach a system suitable for engineering development. OPNAV approved engineering development of the system for initial evaluation on the F/A-18E/F. The Army adopted the NRL missile warning approach as the preplanned product improvement for their Common Missile Warning System. The Director for Electronic Warfare, OSD, identified NRL's demonstrated approach as the eventual tri-service missile warning system.

More recently, in response to a joint urgent operational need, NRL developed, assembled, and demonstrated a highly effective and lightweight infrared countermeasure system that has the capability to protect allied aircraft against infrared-guided missiles. Previous systems were too large, heavy, expensive, and ultimately unreliable for many airborne platforms. NRL's Distributed Aperture Infrared Countermeasures (DAIRCM) system delivers a high-performance missile warning and laser-jamming capability within those constraints to protect aircraft against current and future threats. Equally important, the system is very affordable, costing half of other existing IR countermeasures systems. The House Armed Services Committee has reported that "Navy, Marine Corps, and Air Force all view DAIRCM as part of their long-term strategy for sustainable, cyber-secure aviation survivability against future battlefield threats."

IMPACT: Historically, the biggest threat to military aviation has been heat-seeking missiles and the biggest challenge for airborne countermeasure systems has been achieving adequate performance within the size, weight, power, and cost constraints of an airborne platform. DAIRCM was chosen as a solution to support a Joint Urgent Operational Need (JUON) SO-0010 signed by OSD in 2016. The system is now fielded on five different type model series helicopters for the Navy, the USMC, the Army, and the Air Force.

AN/ALE-50 TOWED COUNTERMEASURES

NRL's earlier development of monopulse radar provided a tenfold improvement in angular accuracy for long-range tracking by fire- and missile-control radars. By the 1970s, however, adversaries had applied monopulse capabilities to their surface-to-air missiles. This created a distinct threat to American aircraft. NRL responded to this threat by developing the Airborne Active Expendable Decoy (AAED), which was an electronic device designed to counter modern radar-guided antiaircraft threats. Laboratory researchers initially explored the development of both towed countermeasures and decoys attached to aircraft-launched missiles for threat deflection. Eventually, towed concepts proved more practicable, and the towed version of the AAED, the AN/ALE-50, was the first towed decoy to be used as an in-flight countermeasure.

The towed-decoy concept differs from the traditional goals of electronic warfare, where antiaircraft missiles are denied the information needed to launch and intercept. Advances in monopulse radars and processing have made this an increasingly hard task. Instead, the towed decoy's effectiveness lies in looking more like an aircraft than the aircraft itself, pulling the threat to itself instead of pushing it away, as in the case for onboard systems.

During the joint Navy/Air Force Multi-Service Decoy Program, flightworthy devices were tested and proved to be extremely effective. Over the years, the AN/ALE-50 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.

IMPACT: At a relatively modest cost of $22,000 per decoy, NRL's AN/ALE-50 made billions of dollars' worth of advanced antiaircraft threats in the hands of the U.S.'s opponents less effective. It has had a dramatic impact on the way U.S. aircraft fly and fight. Before the AN/ALE-50, aircrews were forced to fly low-altitude, "nap-of-the-earth" flight paths to avoid the radar-guided threat, which, in turn, forced them into the envelope of shoulder-fired missiles and antiaircraft artillery. In fact, this decoy protects combat aircraft so well that it earned the nickname "Little Buddy" from our pilots. In the Kosovo campaign alone, 1,479 were used and the system was credited with saving several aircraft.

ANTI-SHIP MISSILE DEFENSE RADAR

In response to the USS *Stark* incident in 1987, and to the increased deployment of U.S. forces in dangerous littoral and other heavy-clutter environments, NRL developed and tested shipboard radars that can detect and track low-radar-cross-section air and surface targets in challenging clutter environments that pose potential threats to naval assets.

Low observable detection and tracking — Beginning in the 1980s, NRL developed the technology necessary for reliable detection of small targets in clutter and demonstrated them using the NRL-developed, high-power SENRAD surveillance radar testbed. The techniques operate the radar at full sensitivity, enabling detection and tracking of small targets at very long ranges. Laboratory researchers designed the transmitted waveform and innovative, new processing techniques enabling the radar to reject echoes from stationary clutter and slow-moving, nuisance targets. The radar was then able to concentrate on the small, high-speed targets of interest and had a low false tracking rate. The technology was transitioned to an upgrade of the AN/SPS-49 radar.

Sea skimmer detection radar — Beginning in 1990, the Laboratory developed the concept for what became the new AN/SPQ-9B anti-ship missile defense radar (ASMD). The concept incorporated a new air mode that provides low-RCS sea-skimmer detection capability and a surface mode with improved performance over the AN/SPQ-9A. An advanced development model was constructed and successfully demonstrated in land-based tests and at sea aboard the USS *Decatur*. This model was able to detect and track sea-skimming missiles near the horizon in difficult littoral environments and had extremely low false-alarm rates. The radar operates simultaneously in both surface and air modes, with the air mode providing an unprecedented clutter-rejection level that was orders of magnitude better than previous technology. The surface mode was able to track small boats and helicopters in heavy sea clutter. 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.

IMPACT: The AN/SPQ-9B radar scans out to the horizon and performs simultaneous and automatic air and surface target detection and tracking of low-flying anti-ship cruise missiles, surface threats, and low/slow-flying aircraft, UAVs and helicopters. It is an important addition to naval sensors in challenging environments such as the Red Sea and the Persian Gulf. The radar is installed on the CVN-68, LPD-17, DDG-51, CG-47, WMSL-750, LHD-1, and LHA-6 ship classes. NRL's low-observable detection technology has been able to provide the AN/SPS-49 radar the ability to detect and track very small high-speed targets through heavy land, sea, rain, and ducted clutter, as well as when large numbers of nuisance objects, such as birds, are present. It provides the Navy the capability to detect and defend itself from attacks from small, high-speed vessels in the littoral environment.

NULKA OFFBOARD COUNTERMEASURE SYSTEM

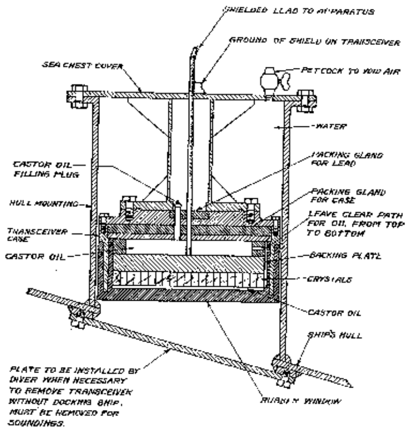
NRL, in partnership with the Australian Defence Science and Technology Organisation, developed Nulka, a quick-reaction offboard electronic countermeasure decoy to defeat anti-ship missiles (ASMs). In 1986, the U.S. and Australia signed an agreement to undertake full-scale collaborative development of the Nulka concept. Nulka faced many hurdles — technical, managerial and political — before it became the state-of-the-art ship-protection system that is now deployed on U.S. and Australian warships.

The project that led to the Nulka decoy originated in Australia in the early 1970s, leveraging NRL's pioneering work on off-board decoys during the 1960s and early 1970s. For example, NRL's Tactical Electronic Warfare Division had undertaken numerous studies on the use of off-board decoys for warship protection, had investigated a wide range of decoy concepts, and had fostered exploratory development of high-performance, low-cost electronic components and devices that could sustain the challenging maritime environment and deployment concepts. By 1995, U.S. Navy fleet commanders were convinced of the system's value. In 1996, the U.S. and Australia began joint production of the Nulka decoys. The early involvement of industry, coupled with the partnership between Australia and the U.S., were key reasons Nulka entered full rate production in 1999.

Nulka is now deployed on numerous Australian and U.S. warships under a program costing around $1 billion. That it took close to 40 years after Nulka was conceptualized testifies to the complexity of the project, which was surmounted by determination and the unique, collaborative relationships between the two countries' R&D and acquisition communities.

IMPACT: The Nulka decoy system is an integral part of the self-defense system against active RF ASM threats on most U.S. and Australian warships. Its incorporation into a layered defense system is essential in providing ship survivability under high-stress conditions in the littoral and open-ocean environments. Because of the characteristics of the decoy payload and the system's fast reaction time, the Nulka system is highly effective against ASMs. The system is effective over a full 360 degrees around the defended ship. The effectiveness of the decoy is independent of ship maneuvers even in the most extreme environmental conditions. Nulka continues to be one of the most effective surface ship EW systems in existence today, protecting forward-deployed forces serving on U.S. Navy and Australian platforms around the world.

FIRST OPERATIONAL FATHOMETER



One of NRL's earliest accomplishments was the development of the first operational depth finder. Today, this device is called a fathometer. The depth finder used two transducers (U.S. Navy MV-type hydrophones), one for transmissions in the frequency range near 1,000 Hz, and the second as a receiver. The measured time interval between the transmitted and received signals, combined with the sound speed, was used to calculate the distance to the sea floor. Use of a directional hydrophone provided the added benefit of determining the slope of the sea floor.

The first acoustic depth finder placed in the U.S. fleet for routine service was installed in the destroyer USS *Stewart* just prior to its departure for Manila via Gibraltar and the Suez Canal in June 1922. Between the U.S. and the Strait of Gibraltar, approximately 900 soundings were recorded, documenting the ocean's depth. Throughout the trip, soundings were taken at least every 20 minutes and at times as often as every minute. The depths encountered were up to 3,200 fathoms (5,900 m). Based on the success of the echo-sounding demonstration on the *Stewart*, depth finders were installed on the destroyers USS *Hull* and USS *Corey* in 1923 and 1924. The destroyers proceeded to make a 35,000 square-mile survey along the coast of Southern California, covering about 1,000 square miles per day. This was followed by installation of the equipment in several more Navy ships. In 1934, improved depth-finding equipment using the QB transducer was installed in the fleet.

Development of the first operational depth finder began in 1919 and was led by H.C. Hayes, who moved his group to NRL upon its opening in 1923. Among the numerous awards received by Hayes was the Navy Distinguished Civilian Service Award (bestowed in 1945 by Secretary of the Navy James Forrestal) and the first Pioneers of Underwater Acoustics Award from the Acoustical Society of America (1959).

IMPACT: 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 U.S. Navy fleet. Its use resulted in greatly enhanced surface and subsurface navigation and surveying capabilities, which improved ship safety.

FIRST OPERATIONAL U.S. SONAR

The submarine came into its own during World War I, most notably in anti-commerce warfare. Ever since, the world's navies have had a keen interest in undersea warfare. The German U-boats, though primitive by even World War II standards, were a deadly, new technology. Given the state of knowledge about sound propagation, there was little that could detect or counter them while submerged. The U-boat fleet destroyed an estimated 5,708 merchant and fishing vessels with a loss of about 15,000 sailors by the war's end. The sinking of the RMS Lusitania, which claimed 1,198 lives, including 123 American civilians, would play a role in the U.S.'s declaration of war on Germany in April 1917.

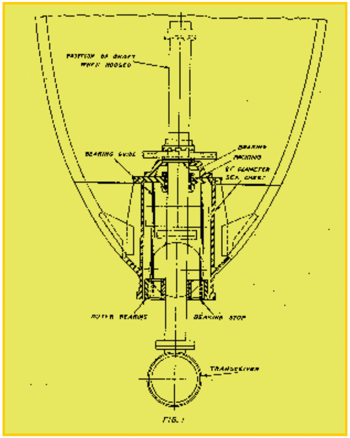


FIG. 1

Underwater acoustic research was started by the U.S. Navy in 1917 with a small group at the U.S. Naval Experimental Station in New London, Connecticut. This group, headed by H.C. Hayes, was eventually moved to NRL on its opening in 1923.

Hayes and his colleagues decided that the passive sonic devices used in World War I were seriously limited in the detection of enemy submarines. It was their belief that active, echo-ranging sonar would provide the best antisubmarine warfare system for surface ships. This approach was taken from the start of the new Sound Division at NRL, where practically all of the U.S. Navy's R&D in sonar prior to World War II was carried out.

NRL's first effort was to develop an improved quartz-steel transducer. Extensive effort was placed on each of the components of the new sonar system, from the transducers and signal processing to the mechanical mounting and housing functions. Of particular significance was the development of the streamlined sonar dome to house the transducer. The dome enabled surface ships to make attacks at speeds up to 15 knots.

In 1927, a number of U.S. naval vessels conducted tests with the NRL quartz-steel echo-ranging sonar. This was the first practical sonar based on the 1918 demonstration by P. Langevin, a French physicist, of the possibility of echo-ranging, or "pinging," at supersonic frequencies. A later system, the Echo Detection Equipment Model QB, became the first operational sonar used by the U.S. Navy.

IMPACT: Sonar transformed naval warfare by improving the ability of surface ships and submarines to detect and track enemy submarines.

FIRST PROPOSAL OF A NUCLEAR SUBMARINE

The use of nuclear power to propel submarines under water was first proposed by an NRL physicist, R. Gunn, soon after fission was discovered by German researchers in 1939. In March 1939, Navy officials, one of whom was Gunn, met with several civilian scientists who felt the military should be made aware of the vast possibilities of nuclear fission. Among the civilian scientists was Enrico Fermi, winner of the 1938 Nobel Prize in Physics. While most of the Navy personnel present at the meeting concentrated their attention on a nuclear weapon, Gunn was conceiving the idea of using nuclear power to drive the world's first nuclear submarine.

NAVAL RESEARCH LABORATORY
ANACOSTIA STATION
WASHINGTON, D.C.

1 June 1939

MEMORANDUM FOR THE DIRECTOR

Subject: Submarine Submerged Propulsion - Uranium Power Source - Status as of this date

1. Under certain special circumstances of bombardment by neutrons, the heavy element uranium dissociates into two other elements with the evolution of tremendous amounts of energy which may be converted directly into heat and used in a flash boiler steam plant. Such a source of energy does not depend on the oxidation of organic material and therefore does not require that oxygen be carried down in the submarine if uranium is used as a power source. This is a tremendous military advantage and would enormously increase the range and military effectiveness of a submarine.

Within a few days after this historic meeting, Gunn had requested and received $2,000 for preliminary work on the possibility of developing nuclear power for ship propulsion. Later, in June 1939, in a memo to the NRL director, Gunn stated,

> "Under certain special circumstances of bombardment by neutrons, the heavy element uranium dissociates into two other elements with the evolution of tremendous amounts of energy which may be converted directly into heat and used in a flash boiler steam plant. Such a source of energy does not depend on the oxidation of organic material and therefore does not require that oxygen be carried down in the submarine if uranium is used as a power source. This is a tremendous military advantage and would enormously increase the range and military effectiveness of a submarine."

In April 1946, NRL forwarded a report to the Bureau of Ships entitled "The Atomic Energy Submarine," which concluded that it was considered feasible to construct atomic power plants of a size and output suitable for ship propulsion. This report also marks the first interest in liquid metal coolants for reactors.

IMPACT: NRL was first to conceive, propose, and investigate the use of nuclear power in submarine propulsion, and through subsequent efforts, the Laboratory contributed to the planning and development of the world's first atomic-powered submarine, the USS *Nautilus*. The nuclear submarine is one of the most formidable weapons systems ever developed.

DEEP OCEAN SEARCH

On April 10, 1963, the nuclear submarine USS *Thresher* (SSN 593) was lost in deep water 260 miles east of Boston, Massachusetts, with 112 crew and 17 civilian technicians. The loss of the submarine and its personnel was a deep shock to the Navy and to the country.

In an effort to determine the reasons for the loss, NRL applied deep-towing technology, developed years earlier for underwater acoustic research, to the deep seafloor search for the *Thresher*. However, the search was terminated in September 1963 with the onset of bad weather. On May 18, 1964, the task group began new search operations. To augment its search capability, NRL had acquired the USNS *Mizar*, a retired cargo ship suited for launching and towing the deep-towed instrument vehicle, or "fish," as it was called. NRL's "fish" included a set of three cameras to photograph the wreckage, a side-scanning sonar to probe beyond camera range, two strobe lights, a magnetometer to locate the *Thresher*'s pressure hull, a transponder, a sonar pinger to measure the "fish's" altitude, and a telemetry system. This unmanned vehicle, towed by *Mizar*, detected the *Thresher*'s hull after only eight hours of bottom operations. NRL's photographs were later assembled into a photomosaic of most of the major parts of the sunken submarine.

After NRL's success in the *Thresher* search, the Laboratory was called upon to locate and recover a lost H-bomb off the coast of Spain in 1966, to locate and photograph the lost submarine USS *Scorpion* (SSN 589) in 1968, to assist in the recovery of the deep submersible *Alvin* in 1969, and to locate and photograph the lost French submarine *Eurydice* in 1970. NRL's emergency-search mission was transferred to other Navy organizations in 1980.

IMPACT: NRL-developed ocean search technology now resides in other government and private organizations. According to a 1966 commendation from the Marine Technology Society, NRL was responsible for "pioneering new techniques" and had "established a methodology for future ocean engineering." Years later, after the RMS *Titanic* was located by Dr. Ballard's team, a former Navy supervisor of salvage stated before Congress that "the superb work of the scientific teams from NRL ... led the way for the [*Titanic*] search operation in the North Atlantic."

SUBMARINE HABITABILITY

In the 1950s, as the age of the nuclear submarine emerged, the requirement grew for extending the capabilities of closed-cycle atmospheres for periods up to 90 days. The need for new atmosphere habitability capabilities was evident when NRL participated in a scientific cruise of the first nuclear submarine, USS *Nautilus*, in 1956. Its atmosphere was found to be “loaded” with pollutants, such as carbon dioxide, carbon monoxide, hydrogen, and hydrocarbons. NRL formed a team to solve the problem. In the 1950s and 1960s, this effort led to the CO/H_2 Hopcalite burner, the monoethanol amine CO_2 scrubber, and the adsorbent carbon bed. The major source of the hydrocarbons was paint thinners. As a result, painting was prohibited immediately prior to submergence and during deployment.

It was also apparent that an analytical instrument was needed to monitor contaminants. In the 1970s, NRL and its private-sector partners convinced the Navy that mass spectrometry was the technique of choice for atmosphere analysis aboard nuclear submarines. NRL evaluated prototype systems that became the basis of the Central Atmosphere Monitoring System Mark-I (CAMS-I). These systems were installed aboard all nuclear submarines, replacing previous, poorly performing analyzers. Later, NRL's research capabilities in mass spectrometry were used to formulate the design of the next-generation analyzer, the CAMS-II. NRL directed the development, laboratory testing, and at-sea trials of the prototype. The CAMS-II is installed in Trident- and Seawolf-class submarines. NRL was also successful in transferring this technology to industry and in convincing the British to use the CAMS-II aboard Royal Navy submarines.

IMPACT: Several NRL technologies led to the purification of submarine atmospheres. CAMS replaced atmosphere analyzers that were always on the “top ten” problem list of submarines. Combined, these technologies enable the Navy to operate its submarine fleet on extended deployments and at the same time to be assured as to the safety of their atmospheres. The commercial version of CAMS, developed by Perkin Elmer for IBM, has been used in semiconductor processing facilities to provide continuous monitoring of a variety of hazardous materials. The advantages of CAMS are its ability to measure many different atmosphere constituents, from parts-per-billion to 100-percent levels, and its reliability. Following the transition of CAMS to industry and the fleet, NRL has continued to address submarine habitability issues by evaluating portable chemical detection devices for use on submarines and verifying the efficacy of the materials control program put into place for the construction of Virginia-class submarines.

FIBER-OPTIC INTERFEROMETRIC ACOUSTIC SENSORS

In 1977, NRL demonstrated the world's first fiber-optic interferometric acoustic sensor. Based on this work, NRL received the first U.S. patent awarded for an optical interferometric sensor to measure external fields. This device focused on acoustic fields. From the beginning, it was viewed as a generic device, in that it would be capable of responding to other external perturbations — electric field, magnetic field, temperature, etc. — depending on the design of the fiber coating or mounting structure.

NRL's work launched Navy, DoD, and national interest in fiber-optic acoustic sensors in particular, and fiber-optic nonacoustic sensors in general. In 1978, based on the fiber acoustic sensor results, NRL conducted the first Navy/DoD program in fiber-optic sensor systems (FOSS) — the vanguard of a rapidly growing interest in fiber interferometric sensors. NRL was the leader in this technology in the late 1970s and early 1980s. Other organizations, such as the Naval Underwater Warfare Center, the Naval Surface Warfare Center, and Litton, joined NRL in developing systems based on these sensors.

A number of sensor system technologies based on interferometric fiber acoustic sensors were successfully demonstrated. One such system was an all-optical towed array (AOTA) with a full complement of fiber-optic acoustic sensors. In 1983, fiber-optic acoustic sensors were first tested at sea. Based on the results, an AOTA Advanced Technology Demonstration was initiated. Successfully completed in 1990, it met all performance goals and showed that the concept was a cost-effective alternative to piezoceramic technology.

IMPACT: NRL's original invention, and the subsequent FOSS program, led to the now-ubiquitous presence of fiber-optic sensor devices. These devices resulting from NRL's pioneering work have been exploited in numerous sensor-related areas, including acoustic, magnetic, electric, thermal, vibration, and flow applications. Commercial versions of these sensors have been applied to traffic control, medical care, construction safety, and seismology. Military applications are also numerous. For example, the Lightweight Wide Aperture Array, a large-channel-count fiber-optic acoustic array, is deployed on the U.S. Navy's *Virginia*-class submarines.

GENERALIZED NEARFIELD ACOUSTICAL HOLOGRAPHY

NRL developed and implemented a new measurement technique called generalized nearfield acoustical holography (GENAH). In 1982, NRL's E.G. Williams began the pioneering work that revolutionized the field of experimental acoustics in noise characterization and control throughout the world. He has since received the Per Bruel Gold Medal for Noise Control and Acoustics (2009) and the American Acoustical Society's Trent-Crede Medal "for development and application of near-field acoustical holography" (2016).

GENAH is the only experimental technique that, from a single array measurement, can provide a complete global analysis of the vibration, radiation, and scattering of structures in air and under water. This provided the Navy with a powerful tool to understand the radiation and scattering of sound from submarines. The understanding of fluid-structure interaction and wave propagation gained through GENAH has been a cornerstone in the Navy's effort to study and remedy acoustic vulnerabilities in the U.S. submarine fleet. This work changed the way the Navy viewed the vibration, radiation, and scattering from submarines and has been a major force in changing the thinking of Navy and non-Navy researchers in their endeavors to quiet the U.S. submarine fleet.

Because of the remarkable scientific and engineering impact of this research, NRL has inspired nearfield acoustic holography efforts throughout the world. In underwater acoustics, the French, Italian, and Japanese navies applied GENAH to study the vibration and radiation of submarines. In architectural acoustics, the measurement technology for studying the transmission of sound through building structures has been revolutionized using GENAH principles in France, while in Japan, new techniques for the measurement of reflection coefficients have been developed. Other transitions of NRL's work have concentrated on noise control in the automotive and aerospace industries, including studies in tire noise and interior cabin noise at laboratories in the U.S., Korea, and Japan. It has also been used to deal with moving noise sources such as cars and trains in France, Korea, and Japan.

IMPACT: NRL's development of GENAH revolutionized the field of acoustic noise characterization and control throughout the world. The U.S. Navy is using NRL's work to reduce acoustic vulnerabilities in the submarine fleet and is applying it to surface ship acoustics. In industry, major acoustical measurement companies have marketed systems based on GENAH for use in a broad range of applications, including noise control in the automotive and aerospace industries. NASA is using GENAH to develop powerful, handheld microphone arrays for real-time interior aircraft noise characterization. Research papers citing NRL's work have appeared in almost every major scientific country in the world.

FIXED-WING AIRBORNE GRAVIMETRY

Measurement and analysis of the spatial variations in the gravity field of the Earth are useful from both geologic/geophysical and geodetic perspectives. Gravity data serve in the first case as a remote sensing probe of shallow and deep mass distributions beneath the surface of the ocean or the land, an important tool for economic geology and basic geophysical research. In the second area, geodesy/gravity data are used to establish the shape and figure of the Earth. Geodetic quantities are of critical operational importance to the Navy, primarily as corrections to high-accuracy inertial navigation systems in submarines and ballistic missiles. Over the years, enormous efforts and expenditures have been devoted to shipboard and terrestrial gravity surveys to meet Navy requirements.

Airborne gravimetry had long been a desirable goal because of the lower costs, rapid collection, and access to logistically difficult areas made possible by airborne surveying techniques. However, the extremely poor signal-to-noise characteristics of airborne gravity measurements defeated numerous attempts since the 1950s by government, academic, and industry researchers to provide airborne data of useful accuracy and resolution. In 1979, NRL began a program in airborne gravimetry from long-range, fixed-wing aircraft. The program required development of extremely accurate three-dimensional aircraft positioning, specialized aircraft operational techniques, and improvements to gravimeter technology. This resulted in the world's first successful demonstration of accurate fixed-wing-based airborne gravity measurements.

IMPACT: NRL's long-range airborne gravity measurement system has provided vital data for Navy and other DoD tactical and strategic systems that cannot be acquired in any other way. Airborne gravity data are collected worldwide to support operational requirements for submarines, ballistic missiles, and aircraft. In other uses, fixed-wing airborne gravimetry was deployed in Afghanistan for a successful airborne remote sensing and mapping project conducted by NRL and the U.S. Geological Survey called Rampant Lion. Building on that success, both agencies completed Rampant Lion II in 2008. Rampant Lion I focused on collecting data that might aid in economic development. Rampant Lion II had an additional goal to support the warfighter. This marked the first deployment of NRL scientists into a combat theater since World War II. The project's impact was significant. According to one U.S. Army officer, "Without the (Rampant Lion Mission) imagery, our missions would not have been successful … on at least five occasions, the imagery was critical to getting us out of tight spots that could have been disastrous."

STRUCTURAL ACOUSTICS

NRL developed structural acoustics (SA)-based sonar technology for search and identification of underwater targets. This new approach has significant advantages over conventional acoustic techniques that rely on kinematic analysis of the scattered returns in the case of anti-submarine warfare (ASW), or the formation of high-resolution images in the case of mine countermeasures (MCM). Also referred to as Acoustic Color, this new technology uses machine learning and a diverse set of "fingerprints" leading to high probability of detection and classification, low false-alarm rates, longer-range operation, and low-frequency sediment penetration leading to the potential buried target prosecution.

SA-based sonar processing has been inserted into a deployed ASW sonar. NRL led a successful rapid response project to apply Acoustic Color to the SQQ-89 sonar system installed on Arleigh Burke-class destroyers. Funded as part of a "Speed to Fleet" initiative, NRL completed the algorithm modifications, software engineering, and at-sea demonstrations in fleet operations within 18 months. The demonstration was carried out aboard the destroyer USS *Fitzgerald* in May 2015.

NRL has also applied this technique to mine hunting using new broadband acoustic sources on autonomous underwater vehicles equipped with its Low-Frequency Broadband (LFBB) technology. The Knifefish system is a part of the MCM mission package targeted to reduce risks to personnel by operating in potential minefield regions as an off-board sensor, allowing host ships to remain at safe distances outside minefield boundaries.

IMPACT: Modern diesel submarines operating in shallow water, on or near the bottom, pose a challenge to the U.S. Navy. NRL's new technology enhances the Navy's ability to conduct undersea warfare without creating an entirely new system. NRL was able to reuse all of the SQQ-89 hardware and much of the existing software of this major fleet system. This provided a low-cost, quick, and successful response to a fleet concern that emerged rapidly. NRL's new technology for the SQQ-89 sonar is also expected to be effective against the emerging threat from unmanned underwater vehicles. NRL's Knifefish system, using LFBB technology, addresses the Navy's need to reliably detect and identify undersea volume and bottom mines in high-clutter environments with low false-alarm rates.

DEVELOPMENT OF HIGH-FREQUENCY RADIO EQUIPMENT

NRL's development of radio equipment in the 1920s, such as quartz-crystal frequency control, high-power transmitters, and receivers, led to the adoption and extensive utilization of high-frequency (HF) communications by the U.S. Navy. Many of these NRL developments were adopted Navy-wide. For example, the quartz-crystal oscillator circuit became the Navy's standard oscillator circuit (1924), and the Model RG receiver was the first to reach the fleet in large numbers, becoming the Navy's principal receiver (1925) for over a decade and continuing in service during World War II.

NRL's HF radio equipment enabled the following achievements that, in turn, facilitated Navy-wide adoption of HF communications.

- An important factor in the Navy's adoption of HF was the performance of the NRL-developed HF transmitter and receiver carried by the Navy's dirigible USS *Shenandoah* during its transcontinental trip in 1924. This equipment accomplished the unusual feat of remaining in communication with NRL throughout the entire trip.
- An NRL HF crystal-controlled transmitter communicated directly with the flagship USS *Seattle* during the cruise of the fleet to Australia in 1925, a demonstration that contributed importantly to the Navy's adoption of HF.
- NRL maintained regular communications with the Antarctic base and support ships of Commander R.E. Byrd's expedition to the South Pole in 1929. The base and ships were equipped with NRL-designed and -fabricated radio gear.

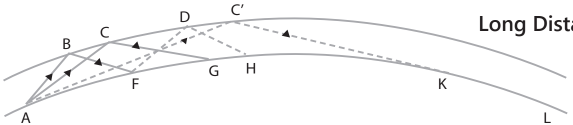
IMPACT: NRL's advances in radio equipment made possible the Navy's adoption of that part of the radio-frequency spectrum known as the HF band (2 to 30 MHz). That technological advance had a profound effect on naval communications for the next 50 to 60 years.

RADIO PROPAGATION AND THE "SKIP-DISTANCE" EFFECT

In 1925, NRL discovered the principles governing the "skip-distance" effect, which, at the time, could not 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. This reflecting layer was the ionosphere, a section of atmosphere that contains charged atoms and ions created by the Sun's energy. Building upon the work of Anglo-Irish mathematician and physicist Sir Joseph Larmor, NRL's A. Hoyt Taylor and E.O. Hulburt jointly published in 1926 a modification of the theory that adequately explained the high-frequency "skip-distance" effect and that agreed with the experimental data.

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. Encirclement of the globe as many as three times in the same transmission and in both directions was observed in 1926. At the same time, reflections of the pulsed HF transmissions from Earth surface prominences, currently called "backscatter," were first observed. These HF "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.

In connection with this high-frequency-propagation work, NRL was also the first to determine the frequency above which radio waves would penetrate the Earth's atmosphere and propagate to outer space, making radio communication in space possible. Taylor and Hulburt determined that, "for radio communication over longer distances, of the interplanetary order, waves shorter than 40 meters would appear to be best able to pierce our own electron atmosphere [ionosphere] as well as that of another planet." NRL would later develop the world's first satellite communication system using the Moon as a relay, which was facilitated by the work of Taylor and Hulburt.



Long Distance Transmission

IMPACT: NRL's seminal work in the field of radio propagation laid the foundation for modern HF wave-propagation theory, led to the Navy's acceptance of HF radio frequencies, which had a profound effect upon naval communications for the next 50 to 60 years, led to the Laboratory's development of over-the-horizon radar, and led to NRL's development of the world's first satellite communication system.

AIRCRAFT RADIO HOMING SYSTEM

When the first aircraft carriers — the USS *Langley* (CV-1) in 1922, and the USS *Lexington* (CV-2) and the USS *Saratoga* (CV-3) in 1928 — became available, there was 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, which was installed on all Navy aircraft carriers and their aircraft and which provided the primary means for aircraft to navigate back to their carriers during World War II. NRL's experimental model was installed on the carrier USS *Saratoga*, the flagship of the Commander, Aircraft Battle Force, then ADM E.J. King in May 1938. After witnessing its performance, King, in a letter to the Navy Department dated August 29, 1938, recommended, "Adopt the (Model YE) system for primary means of homing radio aircraft." As a result, the system was installed on all aircraft carriers and was used extensively in the Pacific during World War II.

The homing system had a dual frequency that confused the Japanese admirals, who realized that U.S. aircraft were successful in returning to their carriers but did not understand how this was accomplished. In one reported incident during a battle in the Marianas, in the waning hours of daylight, when American planes followed the stricken enemy nearly to the limit their fuel would permit, most of the planes and their pilots were saved by homing back to their carriers in the dark with this equipment.

IMPACT: This system had a major impact upon Pacific combat operations during World War II. 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 development. The British also eventually adopted this system for their carrier aircraft. The system continued in use until it was replaced by the TACAN (Tactical Air Navigation) system in 1960.

FIRST OPERATIONAL SATELLITE COMMUNICATION SYSTEM

While conducting its original high-frequency-propagation work in the 1920s, NRL was the first to determine the frequency above which radio waves would penetrate the Earth's atmosphere and propagate through outer space, making radio communication in space possible. Years later, 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 a fidelity adequate for radio communication. NRL then developed the key transmitter and receiver technologies that allowed for effective communication through a passive Moon circuit.

In 1954, NRL was the first to transmit and return the human voice through outer space. NRL first demonstrated transcontinental satellite communication, from Washington, D.C., to San Diego, California, in 1955. The first official message to be transmitted via a satellite was sent over this circuit. The system was then designated "Communication Moon Relay," or CMR. It should be noted that CMR was a spin-off of a classified NRL project, known as "Passive Moon Relay," which used the Moon as a means to intercept reflecting Soviet radar signals.

In 1959, the world's first operational satellite communication system, allowing communications from Washington, D.C., to Oahu, Hawaii, was placed into operation. Public demonstration of this system took place on January 28, 1960 with the exchange of messages between the chief of naval operations and the commander of the Pacific Fleet. The system proved reliable, its main limitation being the position of the Moon. Operators manned the system for a period of four to eight hours daily, the time from moonrise in Hawaii to moonset in Washington. Also in 1960, NRL transmitted the first pictures (facsimile) over a satellite communications system, the CMR.

IMPACT: While the CMR never became a routine communications system, NRL ushered in the age of satellite communications by developing key technologies needed for viable artificial satellite communications. This was of critical value because the U.S. is a global maritime power with naval forces deployed worldwide. Communication with far-flung and constantly mobile forces is critical to American seapower. With the use of satellite communications, a task force commander can stay in contact without relying on vulnerable land lines, undersea cables, and radio relay stations, which are often on foreign soil.

SECURE VOICE COMMUNICATION

A linear predictive coder (LPC) is a means to represent the speech spectrum efficiently. In the LPC representation of speech, the speech spectral envelope is represented by an all-pole spectrum. In 1973, NRL's G.S. Kang developed the world's first LPC prototype capable of operating in real time to encode speech at low data rates. NRL's efforts generated an impetus to modernize DoD tactical secure voice communication equipment. Subsequently, NRL incorporated the LPC concept into the DoD Advanced Narrowband Digital Voice Terminal (ANDVT), which that was under development at the time. Later, Kang incorporated the ANDVT voice encoding algorithm in Federal Standard 1015.

The computational steps required to execute LPC processing were enormous. In fact, it was doubted that LPC could be implemented as a voice communication device. But in 1973, NRL was successful in implementing a real-time LPC telephone operating at 2,400, 3,600, and 4,800 bits per second because the Laboratory had developed a computationally efficient iterative solution to the LPC analysis.

In the 1990s, the DoD introduced a new narrowband voice-processing algorithm called the Mixed-Excitation Linear Predictor for supporting tactical communications. Due to its earlier research in secure voice processing and successful development of the LPC, NRL was asked to find a way to translate the old and new voice data so that old and new tactical phones could interoperate directly. NRL's speech-encoding experts took only six weeks to invent a voice-communication-processing system that provided the needed interoperability, and thus saved the DoD millions of dollars in replacement and transition costs. The resulting algorithm also improved speech intelligibility and was widely disseminated across DoD and NATO for tactical communications.

IMPACT: NRL's development in 1973 of the world's first LPC prototype capable of operating in real time to encode speech at low data rates brought a complete upgrading of military tactical secure voice communication equipment in the 1970s. The LPC-based ANDVT replaced the old channel vocoders. By 2005, 40,000 ANDVTs had been deployed by the Navy, the Air Force, the Army, allied forces, and other government agencies to support tactical secure voice communications. In addition, much of this research into computationally efficient LPC analysis was widely adopted into the cellphone industry and is still utilized today. In the 1990s, NRL's narrowband voice translation system provided direct interoperability between old and new speech parameters, allowing new and legacy ANDVT phones to work together. The result was that 40,000 legacy phones were not retired prematurely and there was no long transition period between new and old systems. Continued use of the legacy units yielded a one-time cost savings of nearly $460 million.

KEY DISTRIBUTION AND MANAGEMENT FOR CRYPTOGRAPHIC EQUIPMENT

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

NRL initiated development of NKDS in response to the Walker espionage ring, whose theft of Navy cryptographic material led to the compromise of many encrypted naval messages between 1967 and 1985. The concept, architecture, and requirements developed by NRL for NKDS changed the paradigm of key material generation, distribution, and management. The NRL requirements called for the replacement of the unencrypted paper key scheme by an electronic system in which keys are encrypted from generation until employment so that their confidentiality and integrity are ensured. NKDS thereby facilitated rapid execution of battlegroup communication plans, improved operational flexibility, and enhanced interoperability with civilian agencies, embassies, and allied coalition nations, as it provided the security needed to protect key material from compromise.

IMPACT: NKDS became operational in 1994 under the Common Tier 1 program established by the assistant secretary of defense for C3I. NKDS became part of the DoD's Electronic Key Management System (EKMS) program, providing the basis for a secure, efficient, and responsive COMSEC Material Control System. Under EKMS, each military service operated its own key management system using common software, based on NKDS, which supported physical and electronic key distribution, traditional electronic key generation, management of material distribution, ordering, and other related accounting and central office functions. EKMS continued to serve as the DoD COMSEC Material Control System until 2013, when it was replaced by the Key Management Infrastructure program.

TACTICAL COMMUNICATIONS

In the 1990s, NRL developed three major items of tactical receive equipment: the Multi-Mission Advanced Tactical Terminal (MATT), the Improved Data Modem (IDM), and the Joint Combat Information Terminal (JCIT). MATT filled a need for a miniaturized multifunction radio and processor that provided near-real-time national intelligence data to field commanders or tactical fighters. The U.S. Special Operations Command selected NRL to develop MATT. The IDM established the first digital data link capability between fighter aircraft and between fighter aircraft and ground units. IDM gave pilots the ability to do in seconds (or less) what used to take several minutes by voice radio, thus minimizing exposure to enemy jamming and/or transmission interception. In 1994, the U.S. Army contracted NRL to develop an airborne tactical operational center (TOC) that was to be housed in a UH-60 Black Hawk helicopter. To meet the Army's needs, NRL developed JCIT. Through the mediation of software, JCIT took the place of the 37 heritage radios, demanding as a consequence only a fraction of the latter's size, power, and weight.

Using knowledge gained through the MATT, IDM, and JCIT programs, NRL designed an interoperable communication infrastructure called InfraLynx. Three days after the September 11, 2001, attacks, NRL responded by integrating InfraLynx architecture into two Highly Mobile Multipurpose Wheeled Vehicles. This allowed first responders to communicate when local infrastructure is destroyed, as was the case with the World Trade Center, or when the infrastructure is completely saturated, as was the case at the Pentagon. InfraLynx platform variations were delivered to the U.S. Northern Command (NORTHCOM), the Federal Emergency Management Agency, the Marine Corps, the Air Force, and others.

More recently, NRL developed the reconfigurable-while-in-operation Software Reprogrammable Payload. This offers cost savings to communications, intelligence, surveillance, and reconnaissance payloads by solving the problem once with a single software infrastructure-and-hardware architecture that can be hosted on land, sea, air, and space platforms.

IMPACT: The Federal Office of Domestic Preparedness adopted InfraLynx. It was deployed to 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, NORTHCOM 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 successfully transitioned to Honeywell International, Inc.

FREE SPACE OPTICS COMMUNICATIONS

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 almost since the development of lasers themselves in the 1960s.

Recognizing the potential application of FSO communications for tactical employment, NRL started two applied research programs in the late 1990s examining gigabit-class FSO, and also a low-size, -weight, and -power (SWaP) FSO technology using modulating retroreflectors. NRL established a test range and began collecting extensive optical propagation data in a maritime environment to ensure the technology would be viable for naval employment.

The research efforts culminated in a demonstration at sea in the Trident Warrior 2006 exercise, with first-generation systems using manual pointing and automated tracking. Two years later, second-generation terminals, with much lower SWaP, were used in exercise Trident Warrior 2008 to demonstrate a modulating retroreflector link. In 2010, NRL commenced the Tactical Line of Sight Optical Networks (TALON) project to develop a third generation of FSO technology specifically focused on a U.S. Marine Corps (USMC) need for modular, compact, affordable FSO terminals. These third-generation systems were delivered in 2013, culminating in demonstration of a 50-km link at China Lake, California, in 104°F conditions — a first for tactical FSO in an eye-safe, affordable form.

In 2016, NRL continued its work on the third-generation systems to fully automate the pointing/acquisition/tracking process to support field use by operational personnel. This effort was funded by proceeds from the third Advanced Wideband Spectrum auction that resulted in the loss of significant amounts of dedicated military radio spectrum, severely affecting the USMC's ability to conduct large-scale training exercises. Proving the military utility of the FSO communications with operational Marines resulted in funding for design and delivery of fourth-generation systems. These efforts are resulting in a game-changing capability that forms a foundation for future expansion to other platforms and operational environments.

IMPACT: NRL's goal has been to develop and verify performance of a fieldable prototype. The advantages of using optical links to augment existing RF communications include: low probability of detection, low probability of interception,, an anti-jam nature, and the potential for very high data rates.

FLYING SQUIRREL

Flying Squirrel is an NRL-developed software application suite that provides real-time discovery, analysis, and mapping of IEEE 802.11a/b/g/n wireless networks and is also capable of scanning for Bluetooth devices. With the advantages that wireless technologies provide, many organizations are seeking the means to securely integrate wireless capabilities into their networks. In an effort to standardize wireless security for the purpose of detecting, and thus deterring, unauthorized wireless activity, the DoD's Enterprise-Wide Solutions Steering Group (ESSG) identified the need to enhance network security through the employment of a wireless discovery device capability. In 2006, the ESSG selected Flying Squirrel as the approved DoD tool for wireless discovery and mapping application.

In order to meet a follow-on requirement for continuous monitoring for threats, a variant of Flying Squirrel called Orb-weaver was developed to fulfill this requirement using multiple fixed sensors. Small, fixed sensor deployments, such as single rooms, to numerous sensor deployments on a large campus, provide continuous wireless monitoring and geolocation for Wi-Fi, cellular, and Bluetooth devices to promote compliance with organizational policies such as a no-cellphone policy. Orb-weaver helps combat the exfiltration of classified and sensitive information over wireless signals by insiders, foreign intelligence activities, and other rogue actors.

IMPACT: Flying Squirrel and Orb-weaver have been adopted and are currently employed throughout the DoD, the intelligence community, federal agencies, and law enforcement, all with a combination of shared goals to detect and geolocate any wireless technology. The U.S. Army's Wireless Security Standards explicitly name Flying Squirrel to perform monthly wireless assessment scans. In the case of overseas deployments, Flying Squirrel is used for Blue Force Protection, ensuring an improved security posture for any forward-deployed units. Law enforcement utilizes Flying Squirrel to detect and geolocate criminal activity, using the results in criminal investigations and prosecutions.

ONION ROUTING AND TOR

The original Internet and original Web protocols were designed without security in mind. NRL invented onion routing as a way to "peel off" and separate identification from routing for Internet connections. Onion routing provides confidentiality and authentication of the route that a connection takes between client and server. It was developed by NRL to protect American intelligence communications online.

NRL research on onion routing and onion services has been ongoing since 1995. In 2004, NRL released Tor (The onion router, so named to distinguish the NRL original from imitators). In addition, Tor introduced onion services. Reachable via an IETF-reserved top-level domain, .onion, these offer authentication and confidentiality of site address lookup, as well as self-authenticating addresses. Unlike ordinary domain names, they are resistant to the many hijacking and man-in-the-middle attacks that have affected sites protected merely by the TLS-certificate and HTTPS encryption infrastructure. In 2016, PrivCount was released. PrivCount has given network researchers, network defenders, and law enforcement a more accurate picture of network usage than was previously possible while reducing the risk to users from either data gathering or the release of resulting statistics.

IMPACT: The public Tor network has grown steadily, currently protecting millions of daily users via a global network comprising thousands of onion routers, transiting an average combined 130 Gbit/sec. Onion service adoption also continues growing. Both Facebook and the *New York Times* offer onion services for improved availability and protection of users wishing to access their sites. Internet services and technology are also increasingly available via onion services, including the DuckDuckGo search engine. While there are criminal elements operating in the "dark web" that use this technology, among Tor's many legitimate users include the military, journalists, whistle-blowers, and citizens from authoritarian regimes. Tor's recognitions include an Electronics Frontier Foundation Pioneer Award and a USENIX Test of Time Award, and its creators were named to the list of 100 Global Thinkers of 2012 by the journal *Foreign Policy*.

WIND-SPEED MEASUREMENT USING MICROWAVE IMAGING

NRL pioneered the use of passive microwave sensing to measure ocean surface roughness and then to use those measurements to derive the surface wind speed. Surface waves, called capillary waves, are excited by the wind. The mechanism is that the wind must have zero speed at the surface so the drag force exerted by the wind is dissipated in these small waves. The interactions between the wind and the capillary waves result in distinct increases in the thermal microwave emission from the ocean. This increase can be measured with a microwave radiometer and the increased emission can then be used to derive ocean wind speed.

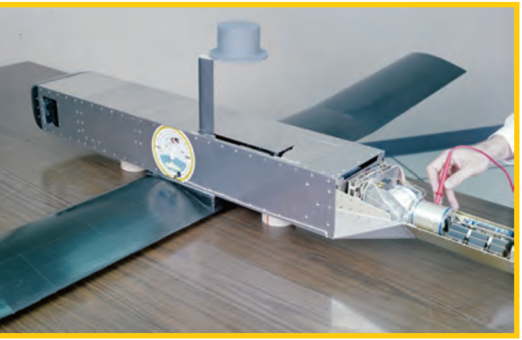
In aircraft and tower experiments from 1966 to 1977, NRL's J.P. Hollinger recognized that this phenomenon could be used to fill the Navy's need to measure ocean winds. He promoted the inclusion of the Special Sensor Microwave Imager (SSM/I) on the Defense Meteorological Satellite Program (DMSP) and set its specification by chairing the DoD specification panel in 1978. The first SSM/I was launched on DMSP F8 in 1987. Hollinger led the calibration validation effort that brought the SSM/I into operational use in 1988.

Following the successful SSM/I series of sensors, an improved version, SSM/IS, or imaging sounder, entered service on DMSP F16 in 2003. NRL's WindSat satellite radiometer built on the success of SSM/I and SSM/IS by adding polarimetry to also sense wind direction. The Weather System Follow-on, DoD's next-generation weather satellite system, is currently in development and includes a polarimetric microwave radiometer capable of measuring wind speed and direction.

IMPACT: The Navy requires ocean wind measurements to provide the U.S. fleet with the most accurate meteorological forecasts possible. Due in large measure to NRL's efforts, satellite passive microwave sensing is the primary operational source of ocean surface wind speed used by both civilian and military forecasters. It also provides data as input to numerical weather prediction models of the Fleet Numerical Meteorological and Oceanographic Center, the National Oceanic and Atmospheric Administration, and the European Center for Medium-range Weather Forecasting.

OPTICAL FIBER GYROSCOPE

NRL was the first to demonstrate long-term inertial-quality performance in a fiber-optic gyroscope. This achievement was a pivotal milestone in the device's development into a practical, precision, inertial-quality navigation instrument that stimulated intense industrial development of the device.



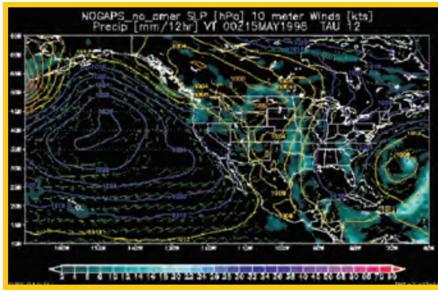
The fiber-optic gyroscope provides rotation sensing for inertial navigation and other positioning and directional applications, such as attitude, heading, and reference in airplanes. The device is used for air and sea navigation and satellite attitude control. Since it provides longer lifetime rotation sensors, it also leads to lower operational cost.

Before 1983, the fiber-optic gyroscope was essentially a laboratory curiosity, with little industrial activity due to limited sensitivity and large bias drifts. The sensitivity problem was solved in Germany by R. Ulrich with the introduction of the broadband source. The bias drift problem was solved at NRL by W.K. Burns and his colleagues, who built one of the first fused-fiber couplers with polarization-maintaining fiber and used this coupler to build a fiber gyroscope with polarization-maintaining fiber. This fiber and coupler greatly reduced the polarization noise that was responsible for long-term bias drift, and performance of 0.035 deg/hr over 24 hours was demonstrated. This result led to the initiation of widespread industrial interest and development efforts, as it demonstrated that the fiber-optic gyroscope was capable of practical inertial navigation. Numerous companies market fiber gyroscopes today that directly incorporate NRL's work.

In 1995, the Institute of Navigation awarded NRL's W. K. Burns the prestigious Thurlow Award for his contributions to the development of the fiber-optic gyroscope.

IMPACT: NRL was the first to demonstrate long-term inertial-quality performance in a fiber-optic gyroscope. The technology replaced spinning mass gyroscopes with fiber optical devices that had no moving parts. This was a revolution in rotation-sensing technology and will have a permanent impact due to higher reliability and longer lifetime, as well as weight, size, and cost reduction. The fiber gyroscope has had significant impact on both military and civilian applications, ranging from use on U.S. military platforms to automobiles. The optical fiber gyroscope is in production in the U.S. as well as in Europe and Japan.

NOGAPS / NAVGEM GLOBAL WEATHER PREDICTION



The Navy Operational Global Atmospheric Prediction System (NOGAPS) and its replacement, the Navy Global Environmental Model (NAVGEM), represent more than 40 years of R&D by NRL. Work on the first of several NOGAPS generations began in 1976. NOGAPS went operational in 1982, and an improved model went operational in 1988. NOGAPS became the DoD's unified global weather analysis/forecast system, used for operational weather prediction around the world. Much of the atmospheric and oceanographic support for military operations had its roots in NOGAPS, whether it was the prediction of cloud cover over the strike target, estimation of environmental effects on weapons systems, the prediction of tropical cyclone formation and movement, or high-seas warnings.

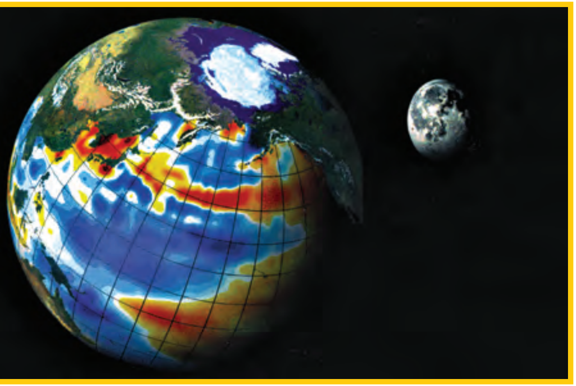
In 2013, NAVGEM went operational, replacing its predecessor. In 2020, NAVGEM transitioned a new, scalable architecture to operations that enabled benefits in terms of price and performance that translated into improved forecasts for the DoD.

NAVGEM provides the world's first prototype of a global numerical weather prediction system extending from the ground to the edge of space. NAVGEM has become the central engine of the Navy's operational weather-prediction system. It feeds data into oceanographic systems such as polar ice forecasts, ocean spectral wave models, the thermodynamic ocean-prediction system, and the prediction of ocean currents. Wind, temperature, and moisture forecasts provide lateral boundary conditions for regional prediction models and tropical cyclone predictions.

IMPACT: NAVGEM supports a wide variety of fleet operations. For example, weather forecasts aid ship and aircraft routing, dust and fog visibility forecasts ensure safety, and predictions of ocean temperature and salinity optimize the efficacy of weapons and sensing platforms. NAVGEM's predictions of the "near space" (~10–100 km) environment support emerging Navy assets such as high-altitude, long-endurance airframes, boost-phase missile defense technologies, and prediction models concerning transport of chemical, biological, nuclear, and radiological material. In 2012, NRL scientists were recognized with the Department of the Navy's Acquisition Excellence Award in Technology Transition. NAVGEM products are used by all branches of the U.S. armed forces, the National Oceanic and Atmospheric Administration, and the Department of Energy.

DECADAL IMPACT OF EL NIÑO

El Niño events in the Pacific Ocean can have significant local effects lasting up to two years. For example, the 1982–1983 El Niño caused increases in the sea-surface height and temperature off the coasts of Ecuador and Peru, with important consequences for fish populations and local rainfall. But until NRL's work in this area, the scientific community believed that the long-range effects of El Niño events were restricted to changes transmitted through the atmosphere, for example, causing precipitation anomalies over the Sahel.



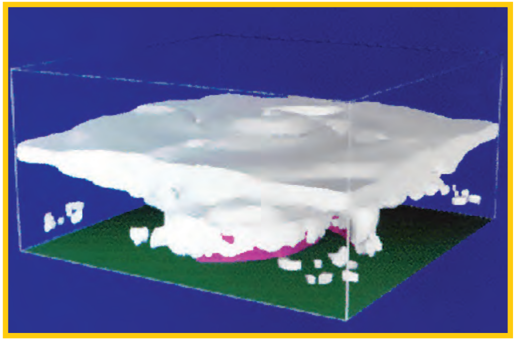
Under the leadership of G. Jacobs, NRL provided evidence from modeling and observations that planetary-scale oceanic waves, generated by reflection of equatorial shallow-water waves from the American coasts during the 1982–1983 El Niño, crossed the North Pacific and a decade later caused a northward rerouting of the Kuroshio Extension (a strong current that normally advects large amounts of heat from the southern coast of Japan eastward into the mid-latitude Pacific). This led to significant increases in sea-surface temperature at high latitudes in the northwestern Pacific of the same amplitude and with the same spatial extent as those seen in the tropics during important El Niño events.

These changes may have influenced weather patterns over the North American continent during the decade following the 1982–1983 El Niño, which may demonstrate that the oceanic effects of El Niño events can be extremely long-lived. It is interesting to note that the most dramatic meteorological event over North America during 1993 was the record-breaking summer rainfall and flooding of the Mississippi river basin. Was this flooding, the worst of the century in the central United States, a delayed effect of the strongest El Niño of the century?

IMPACT: NRL's research showed for the first time that the oceanic effects of El Niño events can be extremely long-lived. The scientific importance of this discovery was noted in an opinion piece by M.J. McPhaden in the same issue of *Nature* as the original Jacobs et al. (1994) article. It was similarly recognized by *Discover* magazine as one of the top 75 science stories in 1994.

MESOSCALE PREDICTION SYSTEMS

The Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®) is the culmination of several decades of collaborative development by NRL's Marine Meteorology and Oceanography divisions. COAMPS provides state-of-the-art high-resolution numerical analysis and short-term (0- to 5-day) predictions of the atmosphere, ocean, and wave conditions for regional domains worldwide. COAMPS development began in 1988 and became the Navy's operational mesoscale atmosphere model in 1998. By 2006, the Navy Coastal Ocean Model (NCOM), the Navy Coupled Ocean Data Assimilation (NCODA), and two-way ocean-atmosphere coupling were integrated into COAMPS. By 2010, the COAMPS coupling layer was extended to include coupling with ocean waves and the Wavewatch III and Simulating Waves Near-shore (SWAN) wave models.



As a result of this multidecade effort, the Navy has a world-class and exclusive capability to conduct new and extensive research on a number of phenomena in which air/sea/wave interactions are an important component of the physical processes, such as with tropical cyclones, explosive cyclogenesis, and electromagnetic and acoustic propagation. The atmospheric component of COAMPS allows for more accurate forecasts over areas that exhibit steep topographic features and strong convection. It predicts tropical cyclone track and structure (COAMPS-TC®) the distribution of aerosols and explicitly predicts water and ice clouds, as well as rain and snow.

IMPACT: COAMPS has supported Navy and DoD operations worldwide over the last 25 years by providing high-resolution predictions of the environment and it is used to drive many tactical applications. 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. Its data are also used by academic institutions and government organizations (including the NOAA/National Hurricane Center, the NOAA/Central Pacific Hurricane Center, and the NOAA Central and Northern California Ocean Observing System).

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.

Mountain wave turbulence is the major global source of severe turbulence for high-altitude, long-endurance Department of Defense aircraft such as U-2s and Global Hawk unmanned aerial vehicles (UAVs). To reach their cruising altitudes of 60,000 to 70,000 feet, such aircraft must eliminate weight and maximize lift, sacrificing some of the heavy structural rigidity of conventional aircraft. This makes them vulnerable to any severe turbulence they may encounter at altitude. These aircraft also have enormous geographical range and thus require global forecasts of atmospheric conditions for safe flight planning.

In response to these challenges, NRL developed the Mountain Wave Forecast Model (MWFM), which is 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. It has been used to direct flights with NASA/European Union aircraft and balloons for studying the physics of polar stratospheric clouds. MWFM provides hemispheric hindcasts of mountain wave effects for global chemical transport models related to the study of the seasonal impact of polar stratospheric clouds on winter ozone loss in the Arctic, and it has provided modeling support for the first observations of mountain waves from satellite platforms.

IMPACT: The MWFM, adopted for operational use by the U.S. 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 and occupants. It was used to predict flight conditions for allied aircraft during operations Southern Watch, Enduring Freedom, and Iraqi Freedom. It was also adapted to run hindcasts of stratospheric mountain wave turbulence over Afghanistan from 1994 to 2001. This was done in order to generate a multiyear climatology of anticipated turbulence levels and geographical distributions in response to requests from the Air Force Combat Climatology Center. In addition, NASA has requested MWFM turbulence forecasts for flight planning during airborne science campaigns with their instrumented DC-8 and high-altitude ER-2 research aircraft.

HYPERSPECTRAL IMAGER FOR TACTICAL AND ENVIRONMENTAL USES

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 system is controlled by the NRL-developed Reconnaissance Management System to enable onboard storage and manipulation and off-board dissemination to ground and sea-based forces in real time via wideband radio links. NRL-developed ground station technology is used to receive and exploit the SHARP imagery. SHARP includes day/night imaging, in-cockpit image review and exploitation, precision geocoordinate determination for targeting applications, and manual or automatic mission execution. The technology is adaptable to manned or unmanned platforms.

NRL has also developed hyperspectral imaging technologies, which have been used to study the environment, to detect man-made objects, and to defeat concealment and camouflage techniques. NRL developed the first gimbal-stabilized shortwave hyperspectral imager designed for long-range operation. The Long-Range Oblique Hyperspectral Sensor (MX-20SW) resulted in the transition of capabilities into operational use in 2010 in Afghanistan via the Radiant Falcon program and in other locations worldwide.

Hyperspectral imaging technologies can also collect data with the resolution and fidelity necessary to address many aspects of the ocean environment that impact naval operations. NRL's Hyperspectral Imager for the Coastal Ocean (HICO) is a spaceborne sensor flown on the International Space Station (ISS). 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 aboard the ISS from September 2009 through September 2014, collecting approximately 10,000 images and greatly exceeding the design's lifetime.

IMPACT: The first SHARP production systems were installed on carrier-based F/A-18 aircraft and were deployed in Operation Iraqi Freedom, Operation Enduring Freedom, and Operation Tomodachi. NRL's prototype predecessor system, TARPS – Completely Digital, was also operationally deployed four times with F-14 squadrons on the USS *Kennedy*, the USS *Truman* (twice deployed), and The USS *Stennis* from 1999 to 2003. Front-line coalition forces received targeting imagery directly. The timelines of this imagery, as opposed to the three-to-nine-day norm associated with predecessor imaging systems, was critical to advancing U.S. objectives and saving coalition lives. The SHARP program development outperformed all previous joint service efforts to rapidly develop, prototype, and field affordable manned and unmanned imaging systems.

GLOBAL OCEAN FORECAST SYSTEM

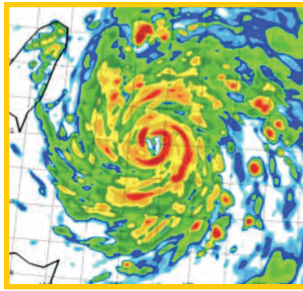
The Global Ocean Forecast System (GOFS) is the U.S. Navy's global ocean prediction system. It runs daily at Commander, Naval Meteorology and Oceanography Command (CNMOC) production centers. The system depicts the location of mesoscale features, such as oceanic eddies and fronts (i.e., the "ocean weather") and provides accurate three-dimensional ocean temperature, salinity, and current structure to the fleet. The first global system was declared operational in February 2006 as GOFS 2.0 and was based on two NRL-developed ocean models, the Navy Layered Ocean Model (NLOM) and the 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 between NRL and academia. HYCOM is unique in that it allows a truly general vertical coordinate, which extends the geographic range of applicability of traditional isopycnic coordinate circulation models toward shallow, coastal seas and unstratified parts of the global ocean. It maintains the significant advantages of an isopycnal model in stratified regions while allowing more vertical resolution near the surface and in shallow, coastal areas, providing a better representation of the upper-ocean physics. GOFS 3.1 was declared operational in 2018 with three new capabilities: a) increased vertical resolution to better resolve the upper ocean, b) two-way coupling between HYCOM and the Los Alamos National Laboratory-developed Community Ice CodE (CICE), and c) improved synthetic profile projection into the ocean interior. CICE provides prediction of the cryosphere that includes sea ice concentration, thickness, and drift forecasts. Lastly, GOFS 3.5 was developed and includes astronomical tidal forcing that produces internal ocean waves at tidal frequencies important to the submarine community.

IMPACT: GOFS provides the Navy with a first look of the three-dimensional ocean environment "anywhere, anytime" across the global ocean. These environmental fields are also used to provide real-time predictions of derived acoustic parameters including sound speed and sonic layer depth. In addition, GOFS provides boundary conditions for higher-resolution regional/coastal models. Ocean forecasts are valuable for tactical planning, optimum-track ship routing, search-and-rescue operations, long-range weather prediction, and the location of high current shear zones. GOFS also provides forecasts of sea ice extent and thickness in the Arctic and the Antarctic. The sea ice environment in the Arctic Ocean has become increasingly important for strategic and economic reasons over the past decade, given the diminishing trend in year-to-year sea ice extent and thickness and the potential summertime opening of the Northwest Passage and Siberian sea routes. Fractures, leads and polynya forecasts are also valuable to the naval submarine community.

REGIONAL TROPICAL CYCLONE PREDICTION SYSTEMS

NRL's Coupled Ocean/Atmosphere Mesoscale Prediction System-Tropical Cyclone (COAMPS-TC) is a regional prediction system designed to generate five-day forecasts of tropical cyclone (TC) track, intensity, and structure. The development of the deterministic COAMPS-TC system began in 2010, and it was implemented operationally at Fleet Numerical Meteorology and Oceanography Center (FNMOC) in 2013. In 2020, the COAMPS-TC Ensemble Prediction System (EPS) was implemented at FNMOC, becoming the first operational high-resolution ensemble-based probabilistic TC prediction system in the world. The COAMPS-TC deterministic system and COAMPS-TC EPS have now supported operations for the Navy and DoD worldwide for a decade.



COAMPS-TC is a highly specialized version of COAMPS, which has been the Navy's operational regional prediction system since 1998. It is a dynamical model, simulating the three-dimensional state of the atmosphere for the TC vortex and the surrounding region, using high-resolution storm-centered moving nested grids. COAMPS-TC uses special algorithms to represent key physical processes in TCs, such as surface drag that occurs at high wind speeds, cloud microphysics appropriate for eyewall convection, and heating from turbulent dissipation. The atmospheric component of COAMPS-TC is coupled to the NRL Coastal Ocean Model (NCOM) to facilitate feedbacks between the atmosphere and the ocean, which are crucial for accuracy in TC intensity predictions.

COAMPS-TC has been upgraded yearly and model performance has dramatically improved. An evaluation of operational forecasts in 2022 revealed that deterministic COAMPS-TC track and intensity predictions are competitive with, and in some aspects superior to, the other leading TC forecast models worldwide. Operational forecasts of Hurricanes Laura (2020), Ida (2021), and Ian (2022), all of which had devastating impact on the U.S. Gulf Coast, highlighted the capability of deterministic and ensemble COAMPS-TC systems to accurately predict these rapidly intensifying TCs, which have been a major scientific challenge. COAMPS-TC has supported numerous ONR-sponsored observational field campaigns: Tropical Cyclone Structure (2008), Impacts of Typhoons on the Ocean in the Pacific (2010), Tropical Cyclone Intensity (2015–2016), and Tropical Cyclone Rapid Intensification (2020–2022).

IMPACT: Tropical cyclone forecasts produced from COAMPS-TC are routinely used by the DoD Joint Typhoon Warning Center and the NOAA National Hurricane Center and are distributed to DoD commands around the world to support mission planning, ship and aircraft operations, and hazardous weather avoidance. The COAMPS-TC forecasts and system are also used by academic and research institutions worldwide.

WINDSAT SPACEBORNE POLARMETRIC MICROWAVE RADIOMETER

NRL's WindSat is the first satellite-based polarimetric microwave radiometer. It was launched in 2003 as the primary payload on the DoD's Coriolis satellite. WindSat's mission was to test and fully 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's 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.

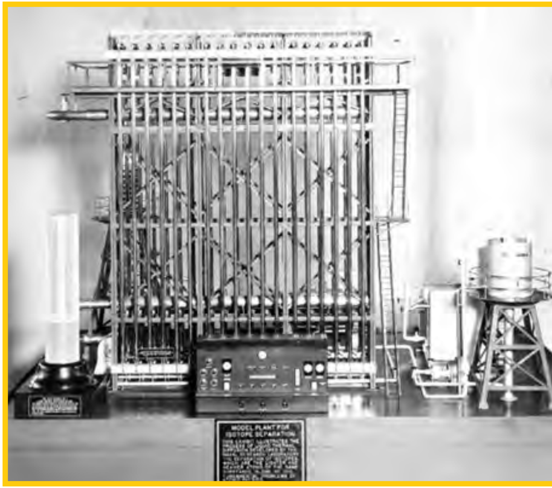
Winds over the ocean affect nearly every aspect of naval operations, including ship routing, carrier operations, and search and rescue. Global ocean winds also provide essential information for short-term weather forecasts and warnings, nowcasting, and climatological and oceanographic studies. For these reasons, the global ocean wind vector had been designated as one of the top meteorological measurement requirements of the Oceanographer of the Navy. WindSat successfully demonstrated the ocean wind vector measurement capability and became a pathfinder for future national weather satellites. In addition, WindSat opened up the field of polarimetric radiometry. One discovery was the relatively strong cross-correlation signals when viewing the ice sheets of Greenland and Antarctica. This potentially offers a new technique for characterizing these environmentally critical regions.

The National Research Council judged Coriolis (Air Force)-Windsat (Navy) to be a model of interagency cooperation in satellite development. Developed for Navy battlespace environment needs, NRL's proof-of-concept system filled a gap in critical meteorological needs as the U.S. military awaits launch of the Weather System Follow-on Microwave satellite.

IMPACT: In more than 17 years on orbit, WindSat far exceeded its original mission objectives. WindSat data was 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. Having more accurate forecasts saves the U.S. Navy millions of dollars annually in storm preparations and avoidance by the fleet.

LIQUID THERMAL DIFFUSION PROCESS

NRL was the first research center that General Leslie Groves visited when he took charge of the Manhattan Project in September 1942. The Laboratory at that time had the distinction of being the first U.S. government agency to support uranium research in 1939. One result of that support was the first successful separation of uranium isotopes by the liquid thermal diffusion process.



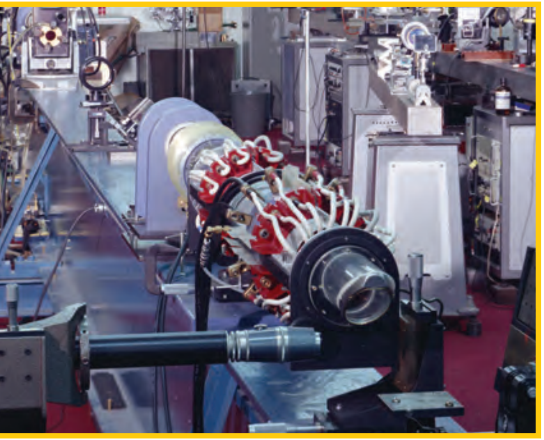
The liquid thermal diffusion process was one of the three methods that the Manhattan Project used to obtain the enriched uranium necessary to form the first atomic bombs. In its early stages, the project employed two enrichment methods, but in 1944, the project hit a technical impasse. When the project's technical director, Dr. Robert Oppenheimer, became aware of NRL's research in using liquid thermal diffusion as a method of separating uranium isotopes, he ensured its use in the Manhattan Project. In June 1944, the blueprints of NRL's liquid thermal diffusion plant were sent to Oak Ridge, Tennessee, and within three months, the first columns of the Oak Ridge uranium separation plant were in operation. In the spring of 1945, Oak Ridge was producing uranium-235 for the Hiroshima weapon.

The Laboratory's contribution was accomplished by a team led by P. Abelson at NRL's main site and later at a larger pilot plant built at the Philadelphia Naval Shipyard in 1943. Abelson had invented the process earlier with NRL funding while he was employed by the Carnegie Institution of Washington. But by 1941, he had become an NRL employee hired to investigate the scale-up of the process. Abelson also invented the first practical method for making uranium hexafluoride, a key material needed for the process of U-235 separation. He would be recognized with the National Medal of Science in 1987 for his "path-breaking contributions in radiochemistry, physics, geophysics, biophysics, and biochemistry and for his vigorous and penetrating counsel on national matters involving science and technology."

IMPACT: The liquid thermal diffusion process was a significant contribution to the success of the Manhattan Project.

HIGH-POWER NEODYMIUM GLASS LASERS

In the 1960s, prior work in France had created Nd:glass lasers with single-pulse energies of about 100 joules and a pulse duration of several nanoseconds. NRL subsequently addressed bridging the gap between hundreds of joules and the tens of kilojoules (kJ) or more needed for meaningful laser fusion experiments. Specifically, NRL recognized how output energy or power density of a disc laser scales with size, recognized the trade-off between laser gain (the amount of amplification), self-focusing, and spatial beam quality, developed a high-gain module and the pulsed-power technology necessary to operate it safely, and developed, built, and demonstrated a laser system comprising these modules that produced a terawatt of peak power per beam. The success of this effort led to the adoption of this technology for the 10-kJ Shiva laser used by the Laser Fusion program at Lawrence Livermore National Laboratory (LLNL).



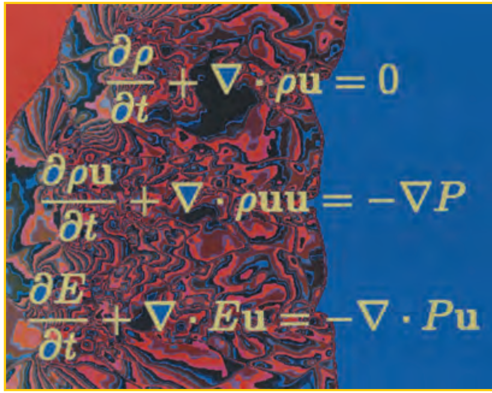
In the late 1970s, the issue became one of how to develop laser designs capable of scaling not to kilojoules per pulse, but to megajoules per pulse. One factor in scaling was the linear and nonlinear optical properties of the host laser glass. Another was the laser performance of the neodymium ion in the particular host glass matrix. A higher-gain laser could function with less glass end to end and hence could tolerate a higher intensity. NRL advocated for the use of phosphate laser glasses to address this issue. The Department of Energy (DoE) supported a test of this scaling concept, which culminated in the successful operation of NRL's Pharos II laser with phosphate laser glass in 1980 at over a kJ. Ultimately, LLNL and the DoE chose to reconfigure the large Nova laser using phosphate laser glasses based on NRL's success.

IMPACT: Between 1966 and 1982, NRL determined how to scale up high-peak-power glass lasers to conditions necessary to perform realistic experiments exploring the potential of inertial confinement fusion. This effort had a major impact on the U.S. laser fusion program. Specifically, it significantly influenced the design of DoE's 10-kJ Shiva laser, the reconfiguration of DoE's Nova laser, and the design of the National Ignition Facility.

FLUX-CORRECTED TRANSPORT

In the late 1960s, NRL conducted theoretical and computational investigations of high-altitude nuclear effects (HANE) for the Defense Nuclear Agency. During 1970 and 1971, to perform this work, NRL had to develop an entirely new technique to solve the fundamental conservation equations describing fluid dynamics computationally. The technique, now called flux-corrected transport (FCT), enabled accurate calculations of strong shocks, high-resolution turbulence, and other steep-gradient phenomena by eliminating the numerical oscillations, ripples, and excess diffusion that had plagued all previous techniques for decades.

In addition to the HANE research, FCT has been employed in missile silo design, nuclear and conventional weapons design, naval oceanography, non-acoustic antisubmarine warfare, and atmospheric communications research. Other uses include research in civil hydrodynamics and water resources, mine safety, atmospheric pollution transport, supernova explosions, solar weather prediction, laser and ion-beam fusion, aerodynamics, and base and force protection against weapons of mass destruction.



IMPACT: With over 1,000 citations, the original paper on FCT was NRL's most cited publication between 1973 and 1988. Over 500 computational laboratories, universities, and companies dealing with fluid flow problems that impact military operations, civil projects, and public health and safety have adopted this technique. More recently, FCT is being used for 3D urban airflow computations that serve as the high-accuracy basis of CT-Analyst®, a faster-than-real-time tool for urban defense against weapons of mass destruction. In fact, this tool was developed at NRL using FCT. A conference entitled "High-Resolution Schemes for Convection Dominated Flows: 30 Years of FCT" was held in Dortmund, Germany, in 2003. Ten years later, in 2013, the journal Computers and Fluids solicited an invited review article on FCT by NRL's J. Boris entitled "Flux-Corrected Transport Looks at Forty" to commemorate this development.

PERMANENT MAGNET MATERIALS

Rare-earth iron boride magnets have had a tremendous impact in the concept and design of devices that use magnetic fields to generate power and to produce motion. Their function as permanent magnets, those that are able to maintain their magnetic orientation at high fields, allows the compact and efficient operation of motors at both small and large scales. Their discovery and use has had the biggest impact in the development of motor technology and the electrification of transportation that directly addresses problems of global climate change and takes advantage of the intrinsic efficiencies of electromotive propulsion over fuel-powered engines.

In 1980, NRL's N.C. Koon and B.N. Das were the first to fabricate and examine the magnetic properties of rare earth-iron-boron (R_2-Fe-$_{14}$B) alloys and demonstrated their promise for permanent-magnet use. This groundbreaking work resulted in fundamental patents that were licensed to several firms and were delivered in commercial products now used in electromotive technology worldwide.

In 1986, N.C. Koon and his colleagues were awarded the American Physical Society's International Prize for New Materials for "*pioneering research on the preparation and characterization of rare earth-iron-boron materials which led to the discovery of a new class of permanent magnets of unusual scientific interest and technological promise*."

IMPACT: Rare-earth iron boride magnets are ubiquitous today in electromotive technology. Since 1983, commercial alloys based on R-Fe-B have been in production at industrial scale, and by 1985, these materials provided almost twice the magnetic energy density of the best materials previously available. It is this property, along with mechanical strength, that has allowed realization of electric motors that compete economically with gas- and diesel-powered engines in performance and with the added benefit of reduced carbon emission — a goal with global impact to fend off global warming.

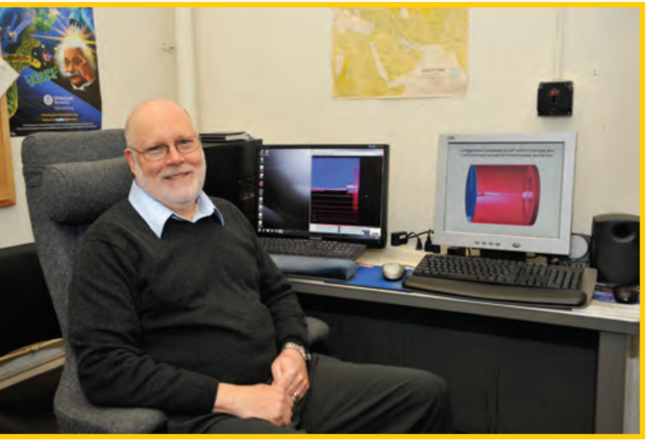
ACOUSTIC MATCHED-FIELD PROCESSING

Matched-field processing (MFP) is a beamforming technique used to localize acoustic sources in a waveguide or to infer waveguide parameters. The conceptual foundation of MFP appeared in a 1961 paper by A. Parvulescu of Hudson Laboratories. The MFP concept was first discussed in an analytic format in 1976 by H. Bucker of the Naval Undersea Center. NRL subsequently began a program to demonstrate MFP's practical viability. In 1981, NRL began research on the MFP concept in the shallow-water propagation environment. In 1983, NRL presented simulations of the MFP concept, now known as the conventional, or Bartlett processor. This processor has become the baseline and most widely used matched-field processor. A pioneering experimental demonstration of MFP was reported by NRL in 1985. This work produced the widely used adaptive, or high-resolution, MFP processor. The conventional and adaptive MFP processors were used as the theoretical basis for MFP shallow-water research programs. The NRL shallow-water work was expanded to the deep-water environment with the initiation of the Office of Naval Technology's High Gain Initiative (HGI). NRL provided much of the theoretical basis and numerical simulation for the research conducted by the HGI from 1988 to 1993. The HGI results suggest that large volumetric acoustic array systems, which use MFP concepts, may be useful for long-range surveillance purposes in deep-water environments.

In a related area, the use of MFP to invert for antisubmarine warfare (ASW)-related environmental parameters received significant attention by the naval research community. These MFP inversion methods were pioneered at NRL and were incorporated into programs directed toward rapid extraction of environmental parameters needed to estimate ASW sonar performance. NRL research included the development of algorithms and the early experimental demonstrations of MFP inversions of ice and bottom properties. One of the first such inversions was for sea ice parameters in the Arctic. The use of global optimization techniques to invert for geoacoustic parameters (a common approach now) was pioneered at NRL.

IMPACT: NRL's early work in MFP provided much of the theoretical and experimental basis for the Navy's HGI, and served as the basis for the design and performance evaluation of large-volumetric-arrays concepts. MFP techniques also led to applications for multiple-line towed arrays. In addition, MFP techniques, pioneered at NRL, for determining geoacoustic parameters in ocean sediments were introduced into the Navy's Oceanic and Atmospheric Master Library. Research into time-reversal techniques and focused acoustic fields had its roots in the early MFP work.

PULSED X-RAY RADIOGRAPHY



NRL enabled breakthrough advances in pulsed X-ray radiography with its invention of the rod-pinch diode in the late 1970s. When a high-current pulse of electrons converges onto the tip of this small-diameter diode, it produces an extremely intense burst of X-rays unmatched by conventional sources. Since 2000, NRL has made significant progress in refining the original vacuum rod pinch. A second-generation version of the diode, the plasma-filled rod pinch, produces an extremely intense X-ray source with parameters previously thought to be impossible with conventional techniques.

IMPACT: NRL's patented device plays a vital role in the Department of Energy's Stockpile Stewardship Program, where it provides images of unprecedented resolution in dynamic experiments studying the performance and safety of nuclear weapons components. In particular, the program requires radiography sources to diagnose the performance of nuclear weapons components at extreme densities and pressures. NRL's device was the X-ray source for the Cygnus generator used in an experiment at the Nevada Test Site that demonstrated a major leap in capability, leading the Los Alamos National Laboratory to state, "Many innovations have combined to lead to this leap in performance, but perhaps the most important has been the effective realization of the rod-pinch diode originally developed at NRL." NRL scientists received two DOE Nuclear Weapons Program Awards of Excellence in 2002 and 2004 in recognition of this work.

GALLIUM NITRIDE TRANSISTOR DEVELOPMENT

NRL's research has been critical to the successful development and application of gallium nitride (GaN) as a next-generation material for semiconductors, which enable advanced high-power capability of radio-frequency transmitters for naval radar and electronic attack. As a semiconductor material, GaN offers many advantages over silicon, the previous industry standard, including higher voltage and power handling, greater efficiency, and improved thermal performance.

Beginning in the mid-1990s, NRL performed pioneering work related to the growth, processing, and practical implementations of GaN material and devices, particularly high-electron-mobility transistors (HEMTs). In 1995, NRL developed an ion implant isolation technique that effectively defined active areas on the wafer that has become an industry standard for GaN microfabrication.

NRL also demonstrated the first AlGaN/GaN HEMTs grown on a high-thermal-conductivity silicon carbide (SiC) substrate. This achievement is a key enabler for high-power devices and has been widely adopted by industry. In 2001, NRL identified trapping effects that were the primary inhibitors to AlGaN/GaN HEMT large-signal performance and developed a surface passivation technique that significantly improved microwave power performance. The surface passivation technique is used today in every GaN transistor.

For over 25 years, NRL has made significant contributions to the development of GaN as a usable material for both defense and commercial applications. In addition to scientific breakthroughs, NRL researchers have provided the Navy and the DoD with subject-matter expertise, device evaluation, reliability testing, and failure analyses leading to the implementation of GaN technology in U.S. defense systems.

IMPACT: NRL's seminal work in the field of GaN materials and devices has laid the foundation for the use of these devices in a number of next-generation systems, including the AN/SPY-6(V) Air and Missile Defense Radar that will be deployed on Flight III Arleigh Burke DDG-51 guided-missile destroyers, in active electronically steered arrays for the Next Generation Jammer, in the Kwajalein Atoll's Space Fence radar for space object identification and tracking, and the AN/TPS-80 Ground/Air Task Oriented Radar.

GAMMA-RAY RADIOGRAPHY

NRL's development of gamma-ray radiography was an important contribution to the nondestructive testing (NDT) of metal castings and welds. The method, devised by R.F. Mehl in the 1920s, entailed the use of gamma-ray radiation as a shadow-graphic technique to detect flaws in cast or welded steels. Using radium as a source of gamma rays and exposure times measured in hours, Mehl and his team were able to image and measure internal cracks in bad castings and welds before the parts failed. This prevented their installation into new vessels. This technique was first used to ascertain the extent of suspected flaws in the sternpost castings of the U.S. Navy's new 10,000-ton heavy cruisers. The integrity of these post castings was vital to the successful operation of the vessels. Such failures could leave a ship at sea unable to steer, a potentially fatal situation. Upon examination, the sternpost castings of these vessels were found to be faulty, and all 10 cruisers of the affected class subsequently had to be repaired to avoid operational failure. During the five-year period before World War II, this NDT technique facilitated the development of improved steel-casting processes. By trial and nondestructive examination, the methods used in all stages of the molding, casting, and testing of steel were improved.

IMPACT: Mehl's work on the Navy's cruiser sternpost castings established gamma-ray radiography as an NDT technique in this country. It also contributed to American seapower by improving the production of high-quality steel for armor, ship frames, and fittings. In 1941, the American Society for Nondestructive Testing originated the biannual Mehl Honor Lecture series to honor R.F. Mehl for his pioneering work in gamma-ray radiography. The selected speaker is chosen for having made an outstanding contribution to the field of NDT. In the years since, gamma-ray radiography has found use in numerous industrial applications such as inspection 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 the flaws, and the material's resistance to failure from them, form the basis for the field of fracture mechanics. Fracture mechanics permitted, for the first time, the capability to calculate the strength of structures containing defects, which inevitably occur in fabrication or during service operation. The net result of these new design principles increased the reliability of structures due to improved design capability and an improved predictive capability of in-service damage.

NRL's G.R. Irwin is recognized as the pioneer of modern fracture mechanics. He developed the scientific principles for understanding the relationships between applied stresses and cracks or other defects in metallic materials. Around 1947, Irwin developedaround 1947, the concept that fracture toughness should be measured in terms of resistance to crack propagation. Critical values of the stress intensity describing the onset of fracture, the commencement of environmental cracking, and the rate of fatigue crack growth were established later. Using these principles, NRL assisted in the solution of critical military and commercial problems, such as the catastrophic failures in commercial jet aircraft in 1953 and fracture problems experienced by the Polaris and Minuteman missile programs in 1957.

A more recent example arose in 1996 when a titanium alloy was considered for the USS *Seawolf*'s muzzle and breech doors instead of the usual steel. Scientists from NRL and the Office of Naval Research were tasked to investigate. They determined that the proposed alloy posed a "risk of unstable, catastrophic failure at the pressure hull boundary." NRL's early work in the 1960s that quantified the sensitivity of titanium alloys to stress-corrosion cracking in seawater formed a basis for the panel's findings. The Navy implemented the panel's proposals.

IMPACT: As a consequence of NRL's pioneering work, fracture mechanics is taught in many graduate schools and remains an active field of R&D today. The principles of this scientific field have been applied throughout 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.

MOLECULAR STRUCTURE ANALYSIS AND THE NOBEL PRIZE

NRL has produced two Nobel laureates, J. Karle and H. 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. The seminal research paper, "The Phases and Magnitudes of the Structure Factors," was published in 1950. The major events leading to the development and adoption of these new methods were quantitative molecular structure analysis in 1948, foundation mathematics for the X-ray phase problem in 1949, and the first general procedure for solving crystal structure problems in 1963. As experience with applications developed, I. 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.

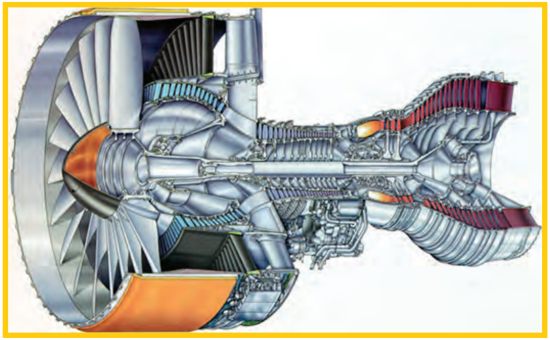
X-ray diffraction analysis involves the determination of the arrangement of atoms in crystals from which the molecular formula is derived directly. Determination of the molecular structure is important in that once the structural arrangement is understood, the substance can then be synthesized to produce useful products. This research occupies an almost 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. I. and J. Karle on their combined 127 years of federal service: *"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."*

IMPACT: Methodologies for determining molecular structures are major contributions to science and technology. For example, they form the basis for the computer packages used worldwide for the analysis of more than 10,000 new substances each year. They have applications to public health, including the identification and characterization of potent toxins found in animals and plants, antitoxins, heart drugs, antibiotics, antiaddictive substances, anticarcinogens, etc. And they support the Navy's energetic materials program, which focuses on making explosives and propellants that are safer, more powerful, or both.

SYNTHETIC LUBRICANTS

Soon after the introduction of gas turbine-powered aircraft in World War II, it became evident that new and better lubricants were required to take advantage of the potential capabilities of these engines. The new lubricants would have to retain sufficient viscosity to support bearing loading at 280° to 300° F and to be stable enough oxidatively and thermally to withstand heat "soak back" temperatures of from 400° to 500°F. Because of NRL's previous success in developing synthetic lubricants for instrument bearings, the Navy Bureau of Aeronautics requested in 1947 that it undertake the development of lubricating oils for turbojet and gas turbines.



Responding to this request, W.A. Zisman, C.M. Murphy, and their colleagues conducted fundamental studies that related molecular structure to lubricating and temperature/viscosity properties. Structural guides derived from those fundamental studies permitted extending the useful temperature range of the oils. As a result, NRL developed the first hydrocarbon ester fluids as lubricants that would perform acceptably at the high bearing operating temperatures in jet engines.

By the early 1950s, diester lubricants developed at NRL were in use in Navy turbine engine aircraft and soon were used by nearly all military and civilian turbine-powered aircraft. As turbine engine power requirements and operational temperatures increased, NRL was active in developing lubricants and lubricant additives to meet these more stringent conditions as well.

In addition to extending the high temperature range, instrument oils were developed for service at -65°F to overcome the problem of aircraft cannon freezing at the high altitudes that were newly reachable by jet aircraft at the time of the Korean War.

IMPACT: The U.S. military needed new lubricants to be able to utilize turbine aircraft at their maximum performance, especially in combat. NRL research met this requirement. Essentially all turbine engines now used by military and civilian aircraft are lubricated with ester oils whose development was based on early research and development at NRL.

POLYTETRAFLUOROETHYLENE FOR THE NAVY

In 1938, while researching Freon compounds as refrigerants, Du Pont researchers discovered that an inert, white solid had formed in one of their gas cylinders that they later trademarked as Teflon. This material — polytetrafluoroethylene (PTFE) — was inert and nonmelting, making it hard to manipulate, but it found early use in the Manhattan Project, as it was able to withstand highly corrosive environments.

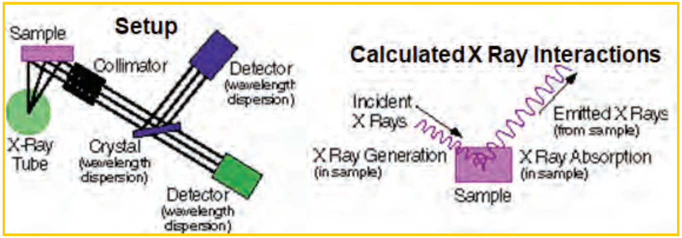
NRL's W.A. Zisman and V.G. FitzSimmons helped Du Pont utilize Teflon as a lubricant and a coating. Teflon's very low coefficient of dry friction was first recognized during cooperative wartime research with Du Pont in 1943. Zisman noted the very low coefficient of friction of thin sheets of Teflon and indicated to W.S. Calcott, director of Du Pont's organic chemistry laboratory, that Teflon had the properties of a practical solid lubricant. NRL collaborated with Du Pont on early sintering experiments that combined Teflon with metal powders and substrates. Through his professional networks in industry, Zisman learned of this novel material, uncovered some of its useful properties, shared these with industry and academe, and developed applications for the new material to exploit its properties for the U.S. Navy's benefit.

IMPACT: NRL worked with the Bureau of Ordnance, the Marine Corps, the Bureau of Ships, and others to investigate the application of Teflon to naval systems and equipment. By 1959, Zisman and FitzSimmo,ns had successfully applied Teflon as dry lubricants and preservatives of steel and brass cartridge cases, with applications to more than 200 different mechanisms on submarines and torpedoes. Zisman noted a wide range of its use by 1968 as a lubricant "in space vehicles, rockets, inaccessible portions of submarines, and in food processing, packaging, and textile machinery. Zisman and FitzSimmons successfully patented PTFE-coating methods for the cartridge casings used in large-caliber (.50 and above) fully automatic rapid-fire guns, as well as PTFE coatings and rings for hard and soft bullets designed to increase barrel life.

QUANTITATIVE X-RAY FLUORESCENCE ANALYSIS

NRL introduced many of the developments that have made X-ray fluorescence analysis (XRF) the quantitative method that it is today. In 1948, H. Friedman and L.S. Birks first outfitted an XRF spectrometer with a Geiger counter, ushering in the era of electronic detection for XRF.

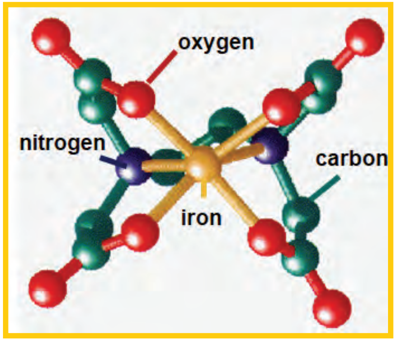
Under the leadership of Birks, NRL brought XRF to maturity by pioneering the use of new instruments such as the electron microprobe, curved crystal spectrographs, and multichannel energy analyzers, and by devising novel analytical methods and computer codes that implement them. Beginning with a calculation of X-ray production in the microprobe, where microscopic standards could not be realized, the codes evolved into a comprehensive software package for quantitative chemical analysis using XRF, incorporating both fundamental parameters and empirical coefficients into a single, flexible program. It has been estimated that by the 1990s, over 1,000 laboratories worldwide had used the NRL software (NRLXRF) or similar programs employing the fundamental parameter approach developed at NRL.



IMPACT: 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 resulted in industrial applications in mining, manufacturing, and metals recycling. This legacy continued with the development of technologies for environmental cleanup and for wear monitoring of high-value machinery. L.S. Birks has been honored with a recurring award established in his name by the Microbeam Analysis Society. In addition, the biennial Birks Award in X-Ray Spectrometry is given by the Denver X-Ray Conference.

IMPROVED BOILERWATER TREATMENT

Naval 1,200 psig 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. Tube failures due to acid corrosion and scale formation are two major concerns that in the past were satisfactorily controlled by a low phosphate/free caustic treatment. However, accumulations of suspended solids required mechanical and chemical cleaning. Both types of cleaning require ships' boilers to be out of service and increase the crew's workload.



NRL and the Naval Ship System Engineering Station (NAVSSES) started investigations into new water treatments to clean, in situ, naval high-pressure boilers in the late 1960s. NRL investigated the thermal stability chemistry of ethylenediaminetetraacetate (EDTA) salts as possible active components of a boilerwater treatment for high-pressure boilers. Nuclear magnetic resonance was used to study the chemistry of EDTA salts and free acid under various thermal conditions. The reported kinetics of the chemical reactions indicated the amount of EDTA to add to the boiler on a continuous basis. This research was the guide that R.L. Dausuel Jr., NAVSSES, used to introduce EDTA into operating U.S. Navy boilers.

This group effort led to a final treatment that included the addition of hydrazine to stabilize the EDTA solutions upon their addition to the boilers. After excellent results from four trial ships, the chief engineer of the Naval Sea Systems Command directed the implementation of a boilerwater treatment based on an Na_4EDTA-and-hydrazine process. Results of shipboard testing demonstrated that use of the Na_4EDTA to clean, in situ, high-pressure steam boilers could extend the normal 1,800 hours of operation between cleanings to 15,000 to 20,000 hours. In addition, the passivated surfaces within the steam systems treated with Na_4EDTA would be beneficial when boilers were shut down for long periods of time.

IMPACT: NRL's basic research was instrumental to keeping U.S. Navy ship boilers in service for much longer periods and in reducing the costs associated with frequent cleanings.

FRACTURE TEST TECHNOLOGY

While NRL's G.R. Irwin was concerned primarily with the basic science of fracture, his colleague W.S. Pellini established methods for prevention of fracture based on experimental methods. Pellini developed engineering approaches for design and material selection in structures based on metallurgical principles. His work solved the mystery of brittle fractures of World War II Liberty ships, in which entire ships sometimes fractured in calm water at dockside, and is still relevant in the age of high-performance ships, aircraft, and missiles.

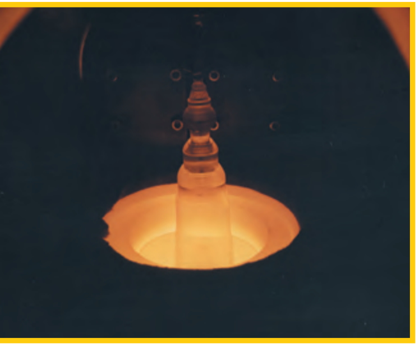
The test methods developed by NRL are the dynamic tear test, the drop-weight nil-ductility transition temperature test (DWT-NDT, standardized by the ASTM in 1963 and used along with the fracture analysis diagram for design of steel structures worldwide), the explosion bulge test, and the explosion tear test. Such tests were incorporated into materials procurement and fabrication specifications for construction of critical submarine and surface ship components. A prominent example is the selection of materials for submarine pressure hulls that had to withstand local deformations from explosive attack without crack extension. NRL worked with the Navy's ship and submarine materials and design codes to develop methods for evaluating materials, weldments, and welding processes. These methods, based on modeling, established the requirements for qualifying welds, welders, and new companies for the construction of submarine pressure hull structures.

The DWT-NDT proved the fracture resistance of HY-80 steel was superior to conventional steels, and the fully plastic performance of welded HY-80 plates in the explosion bulge test convinced the Navy that HY-80 should be used for submarine hulls and for any other critical application. In addition, deep-submergence rescue vehicles that were built with pressure hull material certified to be reliable as measured by fracture mechanics methods were put into the fleet.

IMPACT: For more than 20 years, NRL was recognized as the leading international center for the development of structural integrity technology. During this time, the Navy relied upon NRL's expertise to assure the structural integrity of aircraft, ships, and submarines, and in doing so, to safeguard their crew members. These techniques also increased the performance of naval vehicles, providing such payoffs as reliable deployment of deeper-running submarines.

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 gallium arsenide (GaAs) that were semi-insulating in nature without the need for doping. Because of their high-purity semiconductor and semi-insulating properties, wafers made from these crystals could be used simultaneously as a dielectric and ion-implanted active-semiconductor-layer material to produce high-performance microwave and millimeter-wave devices and integrated circuits. This development was important because transistors and microcircuits made of silicon, the most common semiconductor material used at the time, operated poorly at microwave frequencies. NRL performed the basic process development, demonstrated the principles for achieving the high-purity semi-insulating GaAs substrate, and was instrumental in transferring the technology to industry for commercialization.



This cost-effective method of GaAs wafer production was important because it led to the early adoption of high-performance GaAs devices and monolithic microwave integrated circuits (MMICs) in military microwave and millimeter-wave systems. Cost reduction is also critical to the competitiveness of U.S. companies. NRL's technology was adopted by major U.S. industrial firms, such as Rockwell International, Westinghouse, Texas Instruments, and Hughes Research. In commending NRL's achievement, one U.S. company claimed that in 1980, approximately 100% of the GaAs device industry was in Japan, but that in 1997, the GaAs integrated circuit industry would realize sales of $447M, with American companies representing 65% of that total.

IMPACT: NRL's achievement yielded a key enabling technology for GaAs monolithic microwave integrated circuits. Military systems using these technologies are in all forms of military radar systems, electronic warfare systems, communications systems, satellite systems, and many weapons systems such as the HARM, the Phoenix missile, the AIM-9L, and the AMRAAM. Commercial uses are ubiquitous and include weather and navigation radar, communications systems including cellular and satellite systems, and wireless LANs. The technology demonstrated audited savings to the military for the 10-year period from 1979 to 1989 of over $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 surfaces of ordinary materials. This process, known as ion-implantation metallurgy, has found great application in improving the performance, increasing the corrosion resistance, and reducing friction and wear of critical components such as ball bearings.

The alloy ASA M50 and M50 NIL are the primary bearing steels used by the Navy in its turboshaft engines. Since the Navy operates over salt water, the environment is very corrosive compared to that experienced by Air Force and commercial aircraft. Refurbishment and replacement of bearings, which cost up to $3,000 each in the 1980s, was a significant maintenance expense. Turboshaft bearings must maintain high rolling-contact-fatigue resistance at relatively high operating temperatures; therefore, stainless steel cannot be used. Protection of the bearings with an anticorrosion coating had been unsuccessful due to delamination of the coatings. NRL's research in ion implantation offered an answer to this problem.

Bearings were ion-implanted with Cr ions that produced a 75-nm-thick stainless steel layer on the low-alloy bearing steels ASA M50 and 52100. This improved by a factor of 2 to 10 the service life and shelf life of the expensive bearings and other components for which the downtime required for their replacement is high. This research stimulated a Manufacturing Technology Program for ion implantation of bearings with Cr or Cr+P ions. Results 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 2.5 times. The Navy program demonstrated to three commercial companies in the U.S. and Europe that implantation of rolling-element bearings could be part of their ion-implantation business operations. A primary commercial interest in the process was for instrument bearings. Motivated by the Navy program, the U.S. Army undertook a study of ion implantation of tool steels for helicopter rework. The study was successful and as a result, the Army purchased an ion-implantation facility for installation at a Corpus Christi, Texas, Army helicopter rework facility.

IMPACT: The early NRL work established the state of the art for ion-implantation metallurgy. In one application, NRL's technology led to advances in corrosion protection of ball bearings on naval aircraft, thus providing a solution to an important Navy problem. It also benefitted the U.S. Army and found application in commercial processes.

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. This was done as a means of achieving longer lifetimes for the fuel tanks, cleaner fuels for aircraft and ships, and the elimination of fuel leakage through the porous welds of these large, underground, steel tanks. Each tank holds up to 300,000 barrels of aviation fuel, with the largest being 100 ft in diameter by 250 ft high. To give a better indication of the size of these fuel storage tanks, a 300,000-barrel tank holds enough gasoline to give a 12-gallon fill-up to 1,050,000 automobiles.

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 (fuels), and other corrosive agents. Use of the lining began in 1983; by early 1986, the lining had been installed in tanks at Naval Air Station Pensacola, Florida (four tanks), Corpus Christi, Texas (two tanks), Norfolk, Virginia, and Patuxent River, Maryland, and at Naval Support Facilities at Yokosuka, Japan, Craney Island, Virginia (two tanks), Diego Garcia (two tanks), and Pearl City, Hawaii (five tanks).

In estimating the financial savings of the fluoropolyurethane topcoat, the Naval Facilities Engineering Command performed a life-cycle cost analysis for a 60-year life for the tanks at Craney Island, Virginia. The command included costs for coating installation and necessary replacement, plus periodic cleaning of the tanks. In 1993 dollars, the epoxy coating cost $60,863 per year, a conventional urethane coating cost $40,698 per year, and the fluorinated urethane coating cost $30,144 per year. Based on 18 fuel tanks coated by 1998, the total life-cycle savings for using fluorinated urethane coatings in place of conventional urethane coatings were $11.4M and more than $33M by replacing epoxy coatings.

IMPACT: NRL's fluorinated polymer coating is an effective lining for the fuel tanks at Naval air stations and Naval support facilities. It also saves a significant amount of money over the life of the tanks. The U.S. Army mandates this lining for the same purpose, and the Defense Fuel Supply Center also specifies this coating in all new tanks. Finally, a clear coating of this polyurethane was adopted in 1987 as the standard coating for BRA-22 radomes on all Los Angeles-class submarines because the water-shedding characteristics of the coating provide more rapid access to stable radar when broaching the sea surface.

MAGNETIC MATERIALS AND SEMICONDUCTOR TECHNOLOGY

NRL's G.A. Prinz recognized that the developments in semiconductor materials technology in the 1970s, which permitted atomic control of crystal film growth in ultrahigh vacuum, could be exploited to fabricate new magnetic materials in thin-film form. Furthermore, he saw that the close lattice match between compound semiconductors and the body-centered cubic (bcc) phases of iron (Fe), cobalt (Co), and nickel (Ni) would open the door to integrating these two fields of materials into common monolithic structures. He initiated molecular beam epitaxial (MBE) growth of magnetic materials on semiconductors in 1979 and demonstrated the first MBE epitaxial growth of iron on gallium arsenide in 1981.

NRL's J.J. Krebs carried out the characterization of these new materials. Using the powerful techniques of angularly dependent ferromagnetic resonance, along with magnetic susceptibility and X-ray fluorescence, he generated a detailed description of these new materials, including the interface and surface properties that dominated their behavior. Further work in this field confirmed the general properties of epitaxial ferromagnetic metal films established by the Laboratory's work.

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 Fe/Cr multilayers epitaxially grown on 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 industries, as well as by the military for fuses and perimeter defense. The largest impact will probably be for nonvolatile magnetic memory in computers, which is under development at several corporations within the U.S. as well as abroad in Japan, Germany, France, and the Netherlands.

IMPACT: NRL's pioneering work was a key technology development that enabled the demonstration by researchers located in France and Germany of the giant magnetoresistance effect using Fe/Cr multilayers epitaxially grown on GaAs. Those researchers were awarded the 2007 Nobel Prize in Physics for their work. In the commercial arena, magnetic metal films on semiconductors, exploited for the giant magnetoresistance effect, was generating $10B in sales for sensors in read heads by 1998, and the introduction of magnetic computer memory was projected to impact a market measured at $100B annually. For military applications, this technology promised far better performance of satellites, missile guidance, and aircraft navigation.

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, when it was applied to the USS *Dextrous* (MCM 13), and it produced a significant reduction in surface temperatures during summertime operations in the Gulf of Mexico. Testing demonstrated that LSA not only reduced ship surface temperatures and the load on air-conditioning systems, but it also decreased the ship's infrared signature.

The USS *Dextrous* was relocated to the Persian Gulf, where the paint's solar reflective properties reduced heat buildup, increased crew comfort, and decreased the ship's infrared (IR) ship signature. LCA paint has been transitioned into the fleet, and now all Navy ships are painted with the NRL-designed paint.

IMPACT: LSA paint has reduced solar heating on Navy ships, leading to lower air-conditioning and maintenance costs and greater crew comfort. The paint has reduced the susceptibility of all coated Navy ships to hostile IR sensors and to IR-guided munitions. The per-gallon cost of the LSA paint is virtually identical to the 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 nearly instant "walk on time" and a rapid return to service, typically in minutes, not hours or days, as with other systems. Superior chemical resistance also makes it suitable for the interiors and exteriors of shipboard tanks for fresh water, seawater, fuel, and waste. Added benefits are low environmental impact and longer times between repainting. Typical recoat times for legacy materials was 3–5 years. These new, solvent-free coating systems are expected to have a 20-year service life.

The novel coatings emerged from NRL's basic research program. NRL's long-term relationships with the Naval Sea Systems Command (NAVSEA) and with the paint-and-coatings industry allowed NAVSEA to catalyze the development of these novel coating systems and to get them into service. This is significant, as corrosion costs the DoD more than $20B per year. In 2009, Vice Admiral Kevin M. McCoy of NAVSEA stated, "by September 2009, there will not be a seawater tank painted on a U.S. Navy ship that's not rapid-cure, single-coat process … We're doing that on submarines, on aircraft carriers, and on surface ships, and we're already seeing the savings coming from that." The single-coat process on one submarine alone saves "well over $100,000."

IMPACT: NRL's high-performance corrosion-control coatings have revolutionized tank refurbishment by reducing a three-coat painting process to a single-coat process and by reducing total production time by more than 80% with rapid-cure technology. After over 70 successful demonstrations across 18 platforms, the rapid-cure coatings were mandated for use in all seawater ballast tanks. According to NAVSEA, the potential fleetwide cost savings over the coatings' expected 20-year life cycle is $1.8B. Total savings reach nearly $2B when combining projected savings from the use of NRL-developed remote tank-inspection and -monitoring systems, which reduce the time and expense of inspecting the tanks. 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, which has been implemented fleetwide, continues to make a significant contribution toward reducing the total costs associated with corrosion control for U.S. Navy ships and submarines.

TOPSIDE CAMOUFLAGE AND NONSKID DECK COATINGS

Legacy epoxy-based nonskid coatings and silicone alkyd-based topside coatings used by the Navy are degraded quickly by UV exposure and have relatively short lifecycles, up to 2 years and 3 years, respectively. This degradation results in corrosion seepage, chemical contamination, loss of abrasive profile, and even delamination that may act as foreign object debris (FOD) for aircraft.

In response, NRL developed and transitioned both two-component (2K) and single-component (1K, all-in-one-can) polysiloane-based coatings. In the case of nonskid deck coatings, the coatings possess greater external durability, color retention, and resistance to moisture, hydrocarbons, and detergents. Significantly, a single formulation can be rolled or sprayed for flight decks and walkways of both surface ships and submarines. The coating has been qualified by NAVSEA and has been approved for fleet usage.

Likewise, standard Navy haze gray silicone alkyds have been used on the topsides of Navy surface ships for about 50 years. A weakness of these surface treatments is susceptibility to staining from running rust and soot. NRL has synthesized a novel organosilane polymer that enabled formulation of a 1K polysiloxane system. It provides greater exterior durability (i.e., retention of visual camouflage), chemical resistance, cleanability, and corrosion resistance than both silicone alkyds and recently qualified commercial 2K polysiloxane coatings. It is also easily applied with brushes or rollers by sailors.

IMPACT: Polysiloxane coatings are now mandated by NAVSEA for use in surface ship freeboard and topside superstructure applications. The technology demonstrates both reduced acquisition costs (28% reduction in installed cost) and extended life-cycle performance (3–5 times). This has enabled a culture change in sailor maintenance workload. In 2016, a full-ship application on the USS *Mahan* (DDG 72) showed a 34-fold reduction in sailor workload relative to legacy coated areas. In addition, the single-component polysiloxane coating was sailor-applied (typically a depot-level activity) on the entire exterior freeboard of the USS *Essex* (LHD-2) in 2017. The cost for sailors to apply the coating was less than $100K, a cost avoidance of more than $900K compared to depot costs.

HIGH-TEMPERATURE NONSKID DECKING

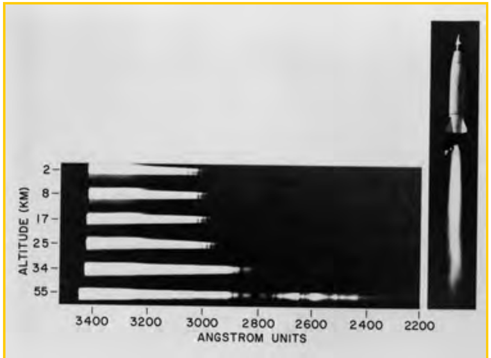
With the advent of vertical-landing-and-takeoff aircraft such as the Joint Strike Fighter (F-35), amphibious landings were anticipated to result in on-deck temperatures high enough to incinerate legacy organic nonskid materials. This was observed during Demonstration Testing #1 (DT-1) on the USS *Wasp* in 2011. In response, NRL developed Thermal Spray Nonskid (TSN), which is an inorganic, nonskid decking that is a robotically applied coating using arc-wire thermal spray processes of commercially available hybrid aluminum/ceramic feedstock. NRL developed and validated the surface preparation, evaluated the relationship of application parameters to performance, and conducted the engineering to integrate thermal spray devices with deck rastering robotics. The resulting systems were tested in scaled jet nozzles with no degradation or erosion through 200 simulated vertical landing cycles. This was later demonstrated aboard ship and showed no degradation through hundreds of vertical landings and multiple deployments on the USS *Wasp*.

Ultimately, this system was used to solve a flight-deck-readiness issue caused by operations of MV-22 and AV-8B aircraft on forward-deployed amphibious-class ships. The issue was elevated to the Marine Corps commandant and the chief of naval operations (CNO) 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-readiness problem. In 2014, at the direction of Fleet Forces Command, NRL led the rapid transition of this technology to the amphibious-class fleet. As neither the NAVSEA acquisition process nor the industrial base was mature enough to support this state-of-the-art process, NRL has spanned the gap as the primary technical expertise to execute the installation of this system on over 125,000 ft^2 on nine ships as of 2020 — USS *Wasp* is programmed to have TSN reapplied after 10 years of service and USS *Bougainville* (under construction) is scheduled for application in FY24.

IMPACT: The development and rapid transition of thermal spray nonskid coating to the amphibious-class fleet resolved a CNO priority for a flight-deck-readiness problem that was curtailing flight operations and was resulting in AV-8B engine casualties. NRL has been widely recognized for this technological development through several awards and commendations from the under secretary of defense for research and engineering, USFF N43, NAVSEA 00, PEO Ships and NAVSEA 05. As noted by the program manager of PMS377, "The integration of the MV-22 and the F35B onto large deck amphibious ships has posed numerous technical challenges ... application of TSN is currently the only way to mitigate these issues."

FIRST FAR-ULTRAVIOLET SPECTRUM OF THE SUN

In September 1945, one leading astronomer confided in another, "If anyone asked you what technological development could, at one stroke, make obsolete almost all of the textbooks written in astronomy, I am sure your answer and mine would be the same, namely, the spectroscopy of the sun outside the earth's atmosphere."



With their wartime experience in research areas as varied as optics, atmospheric scattering, night vision, and optical reconnaissance, NRL physicists such as R. Tousey were prepared to become world leaders in the design of high-altitude spectrographic equipment. 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. NRL was not alone in the early attempts to measure the solar ultraviolet spectrum, as Johns Hopkins University's Applied Physics Laboratory obtained excellent results only six months after NRL.

The successful flight of October 10, 1946, carried cosmic ray detectors, pressure and temperature gauges, radio transmitters, and antennae to measure propagation through the ionosphere, as well as a spectrograph. Although earlier flights had returned scientific data revealing cosmic-ray counts and pressure and temperature information, the successful retrieval of an ultraviolet spectrum of the Sun captured the attention of both the scientific and mainstream press. The *Washington Post* heralded the discovery of the "new ultraviolet" and reproduced samples of two spectra on page one. The *New York Times*, the *Times Herald*, and the *Washington Star* all followed suit.

IMPACT: Scientifically, NRL had extended the known spectrum of the Sun and produced spectra revealing the degree of ozone absorption in the UV. This achievement also marked the birth of space-based astronomy and the U.S. Navy's space program.

FIRST DETECTION OF X-RAYS FROM THE SUN

With the launch of an experiment aboard a V-2 rocket on September 29, 1949, NRL directly 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 rocket flight and two Aerobee firings later indicated that the solar X-ray spectrum is adequate to account for all E-layer ionization. This pioneering research opened the field of solar X-ray astronomy that the Laboratory explored so extensively in the 1950s and thus contributed profoundly to the understanding of the physical processes in the solar atmosphere. A practical benefit of this research includes the improved 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 spaceflight.

NRL's H. Friedman led the Laboratory's pioneering efforts in X-ray astronomy. In 1969, he received the National Medal of Science, the U.S.'s highest honor for scientific achievement, for "pioneering work in rocket and satellite astronomy and in particular for his contributions to X-ray astronomy." Later, in honor of this work, he received the coveted Wolf Foundation Prize for Physics in 1987. The Wolf Prize committee recognized Friedman and the other two corecipients of the award as "... the principal founders of X-ray astrophysics, a new field of astronomical science which has proven to be a prolific source of fundamental discoveries and deeper physical understanding about high-energy processes in the universe. Their work has profoundly influenced every area of astronomical research."

IMPACT: The first detection of X-rays from the Sun marked a major milestone in NRL's continuing endeavor — beginning with E.O. Hulburt's theoretical efforts in the late 1920s, continuing through the SOLRAD satellite series and other satellite programs — to determine the source of the radio-reflecting layer. Observations of solar X-ray emissions are now used to predict the state of the ionosphere and its effect on radio propagation, especially at the HF frequencies. NRL's increasingly refined understanding of the ionosphere has aided in naval communications on Earth and in space, improved missile and satellite tracking, improved telemetering of data from rockets and satellites, played a crucial role in the operation of high-frequency direction-finder systems used to track Soviet submarines, and helps to predict the effects of ionospheric scintillation on GPS satellites.

THE VIKING SOUNDING ROCKET PROGRAM

In 1946, NRL undertook design of a sounding rocket in close collaboration with their contractor, Glenn L. Martin Company. The Viking sounding rocket was the first rocket designed for essentially 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 the 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 U.S.

NRL launched a total of 14 Viking rockets between 1949 and 1957. Viking 4 demonstrated that such a rocket could be handled operationally and launched from a ship, the USS *Norton Sound*, achieving an altitude of 106.4 miles. Launching such a large rocket from the deck of a ship had important national security ramifications in that it was a step toward the eventual deployment of missiles at sea. In fact, *Life* magazine reported that Navy officials had “proved for the first time that big rockets, capable of carrying A-bombs several hundred miles, could be launched from the deck of a ship.”

Viking 7 achieved the highest measurement of atmospheric density and atmospheric winds (136 miles peak altitude). Viking 10 took the then-highest measure of positive ion composition and the highest exposure of cosmic ray emulsions (superseded by Viking 11, which reached a record peak altitude of 158 miles). In 1954, Viking 12 (on display at the Smithsonian Air and Space Museum) reached an altitude of 144 miles and took the then-highest-altitude photographs of the Earth.

IMPACT: Methods for tracking, telemetering data, and rocket design had all been honed in NRL’s decade of sounding rocket research. In many ways, Viking paved the way for the historic Vanguard project, America’s first satellite program. Today, sounding rockets remain a critical platform used to establish the space readiness of satellite instruments and critical platforms for upper atmospheric research.

VANGUARD PROGRAM — THE ROCKET

Between 1955 and 1959, NRL conducted the first American satellite program, called Vanguard. The program was initiated to represent the U.S. in the International Geophysical Year (IGY), a cooperative international scientific effort to study the physical properties of the Earth. The nation's leaders chose to participate in the IGY by placing an artificial satellite into orbit, and a competition was held to determine which government agency would build and launch the satellite. NRL's plan was selected, due in part to its success with the Viking program. The Laboratory's pioneering task was to design, build, launch, place into Earth orbit, and track an artificial satellite carrying a scientific experiment. The contractor for the rocket project was the Glenn L. Martin Company.

The rocket successfully met the program's objective of putting a satellite into orbit during the IGY. The *Vanguard I* satellite was launched into Earth orbit on March 17, 1958, 5 months and 13 days after the Soviet Union launched Sputnik I, and about 6 weeks after the launch of *Explorer I*, America's first orbiting satellite.

Successfully designing and developing a three-stage rocket, with three brand-new and unproven stages, on such a timely schedule was unprecedented. Experience in the DoD at that time showed that in missile programs, it took more than 5 years from the start of a program to arrive at the date of the first successful launching; the Vanguard team achieved their objective in 2 years, 6 months, and 8 days. Wernher von Braun, chief architect of the Redstone rocket that launched *Explorer I* into orbit, called it a miracle. The Redstone rocket was America's first large ballistic missile and it had made its first successful flight in 1953, two years before NRL's Vanguard proposal was approved in 1955.

IMPACT: The Vanguard rocket successfully met the program's objective of launching a scientific satellite into orbit during the IGY, and the rocket technology pioneered by Vanguard was used by later programs. The use of a "strapped down" gyro platform, the rotatable exhaust jets of the first-stage turbopump that ensured efficient roll control, and the C-band radar antenna beacon employed on the Thor-Able vehicle all originated with Vanguard. In fact, the Air Force used many design concepts from Vanguard's second and third stages in its Thor-Able booster. Finally, one of America's most versatile and reliable launchers, the Delta rocket, reflects much of Vanguard's design.

VANGUARD PROGRAM — THE MINITRACK AND SURVEILLANCE

Since a suitable satellite-tracking system did not exist at the time of the Vanguard program, NRL developed the world's first satellite-tracking system (called "Minitrack") in 1956. This tracking network was later transferred to the Goddard Space Flight Center and formed the basis for the satellite-tracking networks used by NASA. Ironically, the Minitrack system first demonstrated its capabilities by tracking another nation's satellite. During October 5–26, 1957, NRL accurately predicted and tracked the orbits of the Soviet Union's *Sputnik I*. Three months later, NRL confirmed and tracked *Explorer I*, America's first orbiting satellite, which was launched into orbit by the U.S. Army on January 31, 1958. Weeks later, Minitrack tracked the orbit of *Vanguard I*, launched on March 17, 1958.

After the Soviet launch of *Sputnik I*, the detection and tracking of foreign satellites orbiting over the United States became a major national-security issue. As a result, the Navy Space Surveillance System (NAVSPASUR) was developed by NRL on a "crash basis" for the Advanced Research Projects Agency from 1958 to 1964 in order to detect and track such satellites. NRL was selected to develop this system primarily because of Minitrack's success. But unlike Minitrack, NAVSPASUR was designed to track satellites that transmitted signals as well as those that were "quiet." NAVSPASUR consisted of nine bi-static radar sites stretching between Southern California and Georgia, constituting a radar "fence" capable of detecting basketball-sized objects in orbit as high as 7,500 miles above the Earth. The information gathered was used to warn U.S. naval units of periods when they would be vulnerable to detection.

By 1983, NAVSPASUR was a critical element in the North American Air Defense Command's Space Detection and Tracking System and was tracking more than 4,966 objects every day. NAVSPASUR was later renamed the Navy Space Sensor System and then became the Air Force Space Surveillance System (AFSSS). After 52 years of service, AFSSS was deactivated in October 2013.

IMPACT: As the world's first satellite-tracking system, the impact of Minitrack was significant, not only to the primary task of tracking the orbits of the Vanguard satellites, but also in tracking the orbits of the Sputnik and Explorer satellites. Later, the concept was employed by NRL in the design and development of NAVSPASUR, the primary system for maintaining surveillance of space objects and for warning U.S. fleet units of periods of vulnerability to foreign surveillance satellites.

VANGUARD PROGRAM — THE SATELLITES AND THE SCIENCE

The *Vanguard I* satellite was successfully launched into Earth orbit on March 17, 1958. Although it was not the first U.S. satellite successfully launched, *Vanguard I* met the program's original objective of putting a satellite into orbit during the International Geophysical Year (IGY), a cooperative international scientific effort to study the physical properties of the Earth. *Vanguard I* achieved the highest altitude of any man-made vehicle to that time and established beyond doubt geologists' suspicions that the Earth is pear-shaped.

A significant innovation in *Vanguard I* was the use of miniaturized circuits. It carried two radios and a temperature sensor and was the first satellite ever to use solar cells as a power source. The solar cells developed by the Signal Engineering Laboratories, placed by Vanguard engineers on the satellite shell so as not to interfere with the functioning of the internal instrumentation, set a new standard of efficiency and account for the long operating life of the satellite. *Vanguard I* orbits the Earth today as the oldest man-made satellite and it will remain in orbit well into the 22nd century.

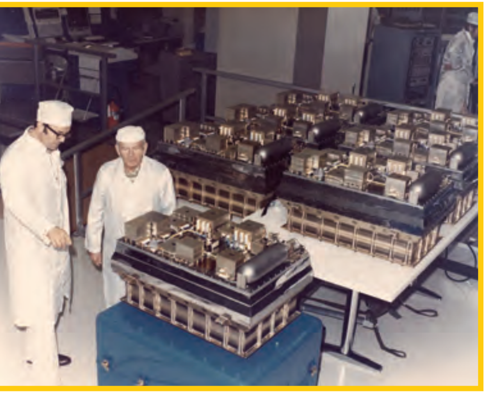
Vanguard II was placed into orbit on February 17, 1959, and was the first satellite designed to observe and record the cloud cover of the Earth. As such, *Vanguard II* was the forerunner of future meteorological satellites.

On July 29, 1958, president Dwight D. Eisenhower signed the National Aeronautics and Space Act, which created the National Aeronautics and Space Administration (NASA). Presidential order 10783 subsequently transferred many of NRL's Vanguard personnel into the newly created space agency on October 1, 1958, where they became a core of technical expertise at NASA's Goddard Space Flight Center.

IMPACT: The Vanguard program established landmark scientific achievements. According to a National Academy of Science panel in 1958, "The overall scientific program developed for use with the Vanguard launching system has made possible the total program of space vehicle instrumentation, observation, and data reduction carried out under IGY auspices. Additionally, it has provided the original basis of the present expanding program of scientific experiments for space research for the U.S."

X-RAY ASTRONOMY

NRL's X-ray astronomy program, led by H. Friedman, dates back to the launch of an X-ray detector on a V-2 rocket on September 29, 1949. That launch was the first of a series of rocket- and satellite-based experiments that determined that solar X-rays are the cause of ionization in the E-layer of the Earth's ionosphere. Following the initial report of significant cosmic X-ray emission in 1962 by American Science and Engineering, Inc., the NRL team expanded their attention to include detection of X-rays from nonsolar astronomical sources.

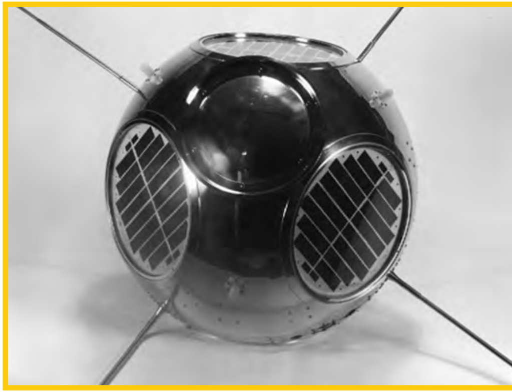


Over a period of three years, NRL conducted a series of sounding-rocket experiments that demonstrated the discrete nature of the X-ray sources and their association with the Milky Way. They showed that the diffuse X-ray background was cosmic in origin. Subsequently, they detected the first extragalactic X-ray source. In one of the most significant rocket experiments flown, NRL researchers observed the Crab Nebula during a lunar occultation of the object and demonstrated that the X-ray emission was emerging from the nebula. This single experiment was the first positive identification of a source of cosmic X-rays with a known object and provided the first observational evidence for the X-ray production mechanism.

NRL produced a sky map of galactic and extragalactic emitters using observations made by an array of large-aperture X-ray detectors on NASA's High Energy Astronomical Observatory (HEAO-1). The resulting *HEAO A-1 X-Ray Source Catalog* included 842 discrete X-ray sources and became a standard reference source for galactic and extragalactic X-ray emitters.

IMPACT: 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 made important contributions to the advance of cosmology and astrophysics. The *HEAO A-1 X-Ray Source Catalog* became an important reference source in X-ray astronomy.

SOLAR RADIATION (SOLRAD) I



The SOLRAD (SOLar RADiation) program was conceived in the late 1950s as an improved means of studying the Sun's effects on the Earth, particularly during periods of heightened solar activity. Of prime interest were the effects of solar radiation on the ionosphere, which had 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, and ten more SOLRADs were fabricated by NRL and flown through 1976.

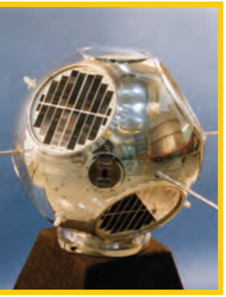
SOLRAD I determined that radio fade-outs were caused by solar X-ray emissions, verifying a theory of NRL's H. Friedman. It was also one of the two satellites launched during the world's first multiple satellite launching and was the first satellite to be successfully commanded to shut off. On August 6, 1960, *SOLRAD I* recorded 6 of 18 minutes of the first solar flare recorded by an orbiting satellite and telemetered the information to a NASA tracking station. The data recorded throughout *SOLRAD I*'s active life shed new light on the relationships among sunspot activity, solar X-ray emission, and radio wave propagation.

Subsequent SOLRADs served as solar radiation monitors circling the Earth, on guard for any unusual solar disturbances that could have endangered astronauts on spaceflight missions. Special SOLRAD operations for the *Apollo 8* mission began at the request of NASA in 1968 when astronauts first circled the Moon. In 1969, solar flare forecasts derived from data furnished by *SOLRAD 9* were used to safeguard *Apollo 11* astronauts and their communication systems during the first lunar-landing mission. NRL provided the data to the Space Disturbance Forecast Center of the Environmental Science Services Administration (now NOAA), which had responsibility for determining the status of radiation hazards to the astronauts. *SOLRADs 9*, *10*, *11A*, and *11B* provided these data throughout the Apollo and SKYLAB programs.

IMPACT: 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 to come 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 U.S. manned space program.

AMERICA'S FIRST OPERATIONAL INTELLIGENCE SATELLITE

The now-unclassified *Galactic Radiation and Background I* (GRAB I) payload, an acknowledged co-flyer with the publicly recognized Solar Radiation I (*SOLRAD I*) scientific payload, was America's first operational intelligence satellite. In June 1960, 52 days after a U-2 aircraft was lost on a reconnaissance mission over Soviet territory, the GRAB I satellite soared into orbit and began transponding space-intercepted electronic intelligence signals to Earth-bound signals-intelligence stations.



GRAB I was the unique application of many emerging technologies. NRL's M.J. Votaw, previously with Project Vanguard, brought the technical experience and resources necessary to design, build, launch, and operate a satellite in space. R.D. Mayo supervised the design and development of the S-band antenna with a crystal video receiver and ground receive equipment to collect signals from Soviet air defense radar. H.O. Lorenzen provided the overall technical direction, obtained intelligence-community sponsorship, and led transfer of the technology into operational deployment. The notion of operating the antenna/detector reconnaissance technology in an orbiting satellite and collecting its transponded signal on magnetic tape was a breakthrough answer to CNO ADM Arleigh Burke's request for naval material bureaus and laboratories to consider how they could use space in their design ideas for the Navy.

With mission sponsorship by the Office of Naval Intelligence, NRL developed the satellite and its network of overseas ground collection sites. President Eisenhower approved the electronic intelligence (ELINT) program and its SOLRAD scientific experiment cover. The GRAB/SOLRAD payloads shared a ride into space with the Navy's third *Transit* navigation satellite as part of the world's first multiple-satellite launching. Field sites recorded *GRAB I* signals on magnetic tapes, which were couriered to NRL for evaluation and duplication. The National Security Agency (NSA) and the Strategic Air Command exploited the tapes for technical ELINT data and to support the Single Integrated Operations Plan.

IMPACT: The GRAB project provided proof of concept for satellite-collected ELINT. 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 operating within the satellite's field of view, at a fraction of their cost, and at no risk to personnel. The output, initially overwhelming, stimulated invention by NRL and NSA of machine processing of digitized data using commercial computers. In searching the tapes for new and unusual signals, NSA found the Soviets were already operating a radar that supported a capability to destroy ballistic missiles. Such information could not be obtained by airborne reconnaissance, nor without enormous risk to human sources. The intelligence information gained from GRAB I had a profound impact on national security decision-making and on deterrence of nuclear war with the Soviet Union.

TIMATION AND NAVSTAR GPS

The NAVSTAR Global Positioning System (GPS) is designed to provide precise navigation data to military and civilian users by means of a constellation of 24 satellites. NAVSTAR is based on NRL's TIMATION (TIMe/navigATION) research program, begun in 1964. R. Easton is recognized for conceiving the idea of the time-based navigational system, which eventually led to the GPS. NRL tested TIMATION concepts by developing and launching two small, experimental satellites, *TIMATION I* and *TIMATION II*.

NRL launched *TIMATION I* on May 31, 1967, and *TIMATION II* on August 30, 1969. TIMATION I demonstrated that a surface vessel could be positioned to within two-tenths of a nautical mile and an aircraft to within three-tenths of a nautical mile using range measurements from a time-synchronized satellite. The TIMATION program proved that a system using a passive ranging technique, combined with highly accurate clocks, could provide the basis for a revolutionary navigation system with three-dimensional coverage (longitude, latitude, and altitude) throughout the world.

In 1973, NRL's program was merged with an Air Force program that was investigating similar techniques to form the NAVSTAR GPS program. *TIMATION III* was redesignated *Navigation Technology Satellite One (NTS-1)* and was launched in 1974 in connection with the new NAVSTAR effort. *NTS-1* carried the first atomic clocks into orbit. *NTS-2* was launched in 1977 as the first NAVSTAR satellite.

IMPACT: NAVSTAR's military and commercial applications are revolutionary and too numerous to enumerate here. In 1993, the National Aeronautic Association selected the GPS Team comprising NRL, the U.S. 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 U.S. 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." In 2005, R.L. Easton received the 2004 National Medal of Technology and Innovation from President George W. Bush for "his extensive pioneering achievements in spacecraft tracking, navigation and timing technology that led to the development of the NAVSTAR Global Positioning System."

REMOTE SENSING OF THE UPPER ATMOSPHERE

The observation of spectral lines in the altitude range from about 120 to several hundred kilometers with instruments developed by NRL's P. Mange during the 1960s and flown on NASA's Orbiting Geophysical Observatories enabled NASA and NRL researchers to recognize the correspondence between UV emission lines from oxygen and local electron density in the ionosphere.

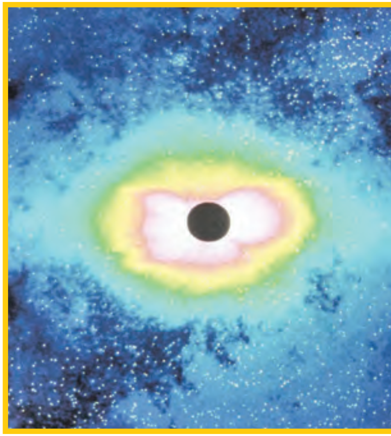
UV images of the Earth taken from the surface of the Moon with the Far UV Electrographic Camera, built by NRL's G. Carruthers for the *Apollo 16* lunar mission, revealed details about arcs of charged particles stretching around the globe — phenomena under study today as the interplay between Earth and space weather. Research by NRL's R.R. Meier in the 1970s provided firm theoretical basis for this correspondence. The UV camera remains on the moon and a backup is on display at the National Air and Space Museum.

Beginning in the 1980s, NRL's work led to new insights and to the design of space instruments for recording atmospheric data and converting them into parameters of interest to the DoD. In 1985, NRL initiated the Atmospheric and Ionospheric Remote Sensing Program, which developed the UV remote-sensing concept. During the 1980s, the DoD Space Forecast Center and the Defense Meteorological Satellite Program recognized that requirements for global atmospheric space weather data were not being met. NRL's Special Sensor Ultraviolet Limb Imager was developed to meet those operational requirements.

Success of these early programs led to further instrument design and spaceflight missions that included UV sensors, near-UV/visible sensors, and GPS radio occultation sensors. The continued investment of remote-sensing-spaceflight-sensor technology, coupled with the advent of small satellites, has led to an evolution of atmospheric sensing, reducing the size, weight, and power of the instrumentation.

IMPACT: Global remote sensing of the upper atmosphere now produces global maps of electron density, neutral density, temperatures, and winds. This capability provides the basis for a new kind of forecasting of upper atmospheric and "space weather" characteristics, much as global measurements of cloud cover led to greatly improved tropospheric weather forecasting. For his invention of the Far UV Electrographic Camera, G. Carruthers received the 2011 National Medal of Technology and Innovation from President Barack Obama.

SPACEBORNE SOLAR CORONAGRAPHS



Study of the Sun's corona, its outermost atmosphere, is a fundamental aspect of solar science. At first, the corona could be seen only during the brief interval of a full solar eclipse. Ground-based telescopes allowed regular observations of the corona, but close to the Sun's surface. With the advent of space-based instrumentation, routine observations out to large distances from the Sun became possible. 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.

On December 14, 1971, the orbiting 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. This was a major discovery. A new phenomenon, called the coronal mass ejection (CME), was born. The measured speed of the outburst was about 600 miles/s and its estimated size was many times the size of the Earth. The frequency and the space weather impact of such events were established by NRL's SOLWIND coronagraph, which was 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 CMEs produce geomagnetic storms at Earth, explained the relationship between flares and CMEs, and established the magnetic flux rope as the probable configuration. LASCO still operates today and helps to predict CME arrival times at Earth.

IMPACT: Spaceborne solar coronagraphs are essential to space weather models of CMEs. NRL was first to demonstrate the existence of CMEs and their role in major geomagnetic storms, 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 discovery led to operational space weather. In 2018, the Secretary of the Navy directed that "DON organizations shall promote investment in associated technologies that ... manage, reduce, or mitigate impacts from ... space weather events, including CMEs."

MARITIME DOMAIN AWARENESS

NRL developed a spaceborne computer in the 1990s that, at the time, was 100 times more capable than anything else flying. By doing so, the On-Board Processor (OBP) program achieved an unparalleled advancement in support of military operations for multiservice and multinational tactical and strategic users. NRL's program included total concept development, system engineering, hardware development, algorithm development, fabrication, testing, and deployment. From 1996 through 2002, it was the largest supplier of tactical data to the military.

NRL's subsequent efforts in the area of multi-intelligence data automated ship tracking has revolutionized the way the intelligence community (IC) and the Department of Defense (DoD) monitor maritime vessels throughout the world. This web-based enterprise effort began in 2004 as a proof-of-concept activity called the Vessel Tracking Program. It demonstrated that automated ship tracking was feasible and led to a demonstration program that advanced the capability of global maritime domain awareness (MDA).

NRL's later development of web-based Sea-Link Advanced Analysis (S2A) advanced MDA from tracking hundreds of objects daily — using humans in loop to correlate data over time into tracks — to automatically producing hundreds of thousands of tracks daily, allowing users in the Navy, the DoD, and the IC to spend more time assessing vessel intent and threat. The history of tracks produced by S2A provided the ability to determine patterns of life and prediction tools for vessels. S2A is a force multiplier for MDA within U.S. and coalition-partner operations.

A related effort was the development of Pirate Attack Risk Surface (PARS), a guidance tool created due to an increase in pirate activity within the Somali Basin Region and the Gulf of Aden that threatened maritime security and stability in these regions. PARS integrates environmental conditions, pirate concept of operations, commercial shipping information, and all relevant piracy intelligence to produce a probability forecast of shipping vulnerability to pirate attack as a function of latitude, longitude, and time. The tool enabled operators to focus on regions where their efforts were likely to be the most productive.

IMPACT: From 1996 through 2002, the OBP was the largest supplier of tactical data to the military. The OBP provided, for the first time, real-time situational awareness information not available with either organic assets or other systems to military units located throughout the world. NRL's subsequent efforts revolutionized the way maritime vessels are monitored globally. MDA advanced from tracking hundreds of objects daily using humans in loop to automatically producing hundreds of thousands of tracks daily, allowing users in the Navy, the DoD, and the IC to spend more time assessing vessel intent and threat.

DEEP SPACE PROGRAM SCIENCE EXPERIMENT (CLEMENTINE)

The Deep Space Program Science Experiment (Clementine) was a highly successful lunar mapping mission. During the 1980s, the Ballistic Missile Defense Organization developed advanced sensor and component technologies for missile defense systems. In 1991, a joint NASA/DoD study concluded that a collaborative deep-space mission could test these developments and could provide a significant science return. The DoD's goals were to test lightweight, miniature sensors and components by exposing them to a long-duration space environment while obtaining imagery of the Moon and the near-Earth asteroid Geographos. NRL was tasked with responsibility for mission design, spacecraft engineering, spacecraft manufacture and testing, launch vehicle integration, terrestrial support, and flight operations.

In 1994, NRL put a satellite equipped with a sensor payload into orbit around the Moon. The spacecraft successfully used much newly developed hardware, including imaging sensors provided by Lawrence Livermore National Laboratory. A high-quality mapping mission of the lunar surface was completed with outstanding success — a complete imaging of the lunar surface (1.8 million images) in 11 discrete wavebands with coarse altimetry over most of the surface. After completing the lunar mission, Clementine suffered an onboard malfunction that prevented it from performing the flyby of Geographos.

This imaging of the Moon's surface was a great success in its scientific returns: the relative positions of widely separated lunar features could be accurately determined for the first time, including those on the Moon's far side, some regions in the lunar south pole were imaged with good resolution for the first time, with some data indicating the presence of ice, and complete multispectral imaging provided information on local mineral composition over the entire lunar surface. Finally, these images helped resolve issues such as the character and evolution of the primitive lunar crust, the thermal evolution of the Moon and lunar volcanism, and the impact record and redistribution of crustal and mantle materials. Clementine's images were made available for students everywhere to explore in a 3D interactive environment on the Internet.

IMPACT: With Clementine's success, the U.S. 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" was attainable: it was built in only 22 months (less than half the usual time) for 1/5 the usual cost for similar space probes. The probe was so simple to operate that its mission control center comprised eight engineers working in a warehouse in Alexandria, Virginia. As for the presence of ice on the Moon, NASA's Lunar Prospector mission in 1998 found evidence of ice at both lunar poles.

INTERFEROMETRY AT OPTICAL WAVELENGTHS

NRL developed techniques to coherently combine light detected simultaneously over a broad bandpass with several independent telescopes. This overcomes the limitations imposed by atmospheric turbulence and physics on the angular resolution achieved with a single telescope or aperture. Turbulence in the Earth's atmosphere had limited the resolution of imaging systems to that achieved by an aperture 4 inches in diameter, or a spatial resolution of 1 arc second (10^{-5} radians). To achieve higher resolution, a larger number of spatial frequencies must be coherently sampled before temporal effects cause a change in the image. This was accomplished by using low-noise photodetectors, laser metrology, precision delay lines, and high-speed computing to detect and compensate for wavefront distortions caused by the atmosphere on time scales of a millisecond.

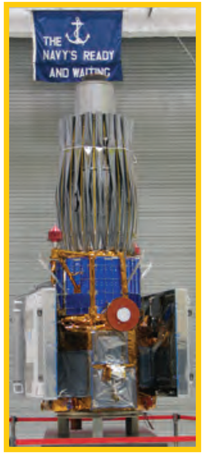
The development of these techniques started with a two-element interferometer at Mount Wilson (1984–1990) and was then expanded into the Navy Precision Optical Interferometer (NPOI). Construction of the NPOI happened from 1989 to 1998, resulting in a system capable of combining light from up to six telescopes separated by up to 435 m, allowing for the development of wide-bandwidth synthesis at optical wavelengths. The NPOI is capable of imaging at spatial resolutions as high as 10^{-9} radians and has achieved images at 10^{-8} radians resolution, easily exceeding that obtained with a single aperture. This work revolutionized the field of optical interferometry, demonstrating several observational and postprocessing techniques that became standard in the field and allow for routine high-angular-resolution imaging of targets.

IMPACT: NRL's development of wide-bandwidth imaging at optical wavelengths is equivalent to the invention of the telescope, with techniques that will be employed in future astronomical and remote-sensing systems. Based on these techniques, the NPOI has been able to fulfill the Navy's positioning, navigation, and timing needs and to determine high-precision fundamental stellar parameters, such as mass, luminosity, and age, which are essential for refining stellar atmosphere and evolution models and for determining properties of planets around other stars. The NPOI has also played a key role on space surveillance and intelligence-gathering systems with the first detection of optical interferometric fringes from a glinting geostationary communications satellite during a favorable Earth-satellite-Sun alignment. The results from this effort guided the development of the Amon Hen project, a hypertelescope that will be capable of obtaining direct images of geostationary satellites on a routine basis. The capabilities developed in this program will allow military systems to see farther with higher definition, allowing larger standoff distances from targets and objects of interest.

TACTICAL SATELLITES

By 2002, a variety of technical developments prompted NRL and the DoD Office of Force Transformation (OFT) to study the potential of tasking space assets for tactical operations. A number of emerging technologies and processes combined to make the OFT's Operationally Responsive Space (ORS) initiative a timely pursuit. For space assets to become operationally responsive in the event of sudden crises, rapidly deployable spacecraft must be available to support U.S. military operations anywhere on Earth, adaptable to payload and orbital constraints.

ORS ran as a series of experiments, with NRL serving as the program manager for TacSat-1, the first experiment of the initiative, which served as the pathfinder for a series of experiments. TacSat-2 and TacSat-3 were Air Force-led, with multiple NRL experiments aboard, and were launched in 2006 and 2009, respectively. NRL was the program manager for Navy's TacSat-4 spacecraft, which was launched in 2011. It operated until February 2013. TacSat-4's mission was to augment operational communications. It provided ten UHF channels allowing communication on the move, data exfiltration, and Blue Force tracking. The unique orbit augmented geosynchronous communications by providing near-global, but not continuous, coverage. The Virtual Mission Operations Center tasking system allowed tactical tasking and dynamic reallocation, within 24 hours, to different theaters worldwide when unexpected operations or natural events occur.



IMPACT: The TacSat program put new capabilities into the hands of operational users in order to advance technologies and concepts of operations, as well as to provide operational value. In particular, TacSat-4 demonstrated that small satellites can provide SATCOM services to naval and joint military forces, and civil defense agencies using their standard equipment, in high latitude and geographically denied locals. TacSat-4 was a smaller, cheaper satellite that could be launched in geosynchronous or nongeosynchronous orbit to augment coverage or to provide coverage outside the area covered by geosynchronous satellites. Trident Warrior 2012 (TW-12) was the capstone experiment for TacSat-4. TW12 established that TacSat-4 was capable of providing UHF and data support to operational users including communication on the move to the warfighter. It provided reliable IP connectivity for voice and data communications. Insights on the utilization of a satellite in a nongeosynchronous orbit were obtained, including antenna setup for communication windows determined by the orbit. The key point is that a small constellation of TacSat-4 class spacecraft would offer significant military utility for UHF satellite communication augmentation in the high northern latitudes to partially fill northern-latitude communication gaps.

DRAGON EYE

NRL, in collaboration with the Marine Corps Warfighting Laboratory, 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 went from a paper sketch to an operational system in 30 months. Prototype evaluation began in 2001. Production aircraft were deployed in Iraq and Afghanistan by 2004.

Dragon Eye was developed as a follow-on effort to the MIniature Tactical Expendable (MITE) micro-unmanned-aerial-vehicle effort within NRL. The MITE effort focused on the capabilities that a micro unmanned aerial vehicle could provide the warfighter, primarily in the areas of over-the-hill reconnaissance and close-in electronic-warfare missions.

Dragon Eye consisted of a man-portable, 5.5-lb., hand-launched, aerial vehicle with the radar signature of a bird. A miniature ground control station provided command and control and received the aircraft's video and GPS position. The vehicle flight characteristics permitted operational use in adverse weather conditions, and the autonomous flight capability allowed one-person operation.

IMPACT: Dragon Eye was successfully transitioned to the Marine Corps Systems Command, and preproduction units were deployed with the 1st Marine Expeditionary Force in Iraq during Operation Iraqi Freedom (OIF). These units provided critical intelligence to American forces in the field. A post-OIF review from the 1st Marine Division noted that on-site intelligence delivered by Dragon Eye proved to be the conspicuous bright spot in overall OIF intelligence-gathering. Dragon Eye was mentioned in a New York Times front-page article about the U.S. Marines' fight for Falluja. By 2010, a total of more than 1,300 Dragon Eye aircraft, designated RQ-14A, had been deployed. In 2008, the Smithsonian's National Air and Space Museum debuted an exhibit showcasing Dragon Eye, along with five other military unmanned aerial vehicles. Also on display were Dragon Eye's computer controls, a parts-and-tool kit, and a bungee-cord launching system.

HYDROGEN FUEL CELLS FOR UNMANNED SYSTEMS

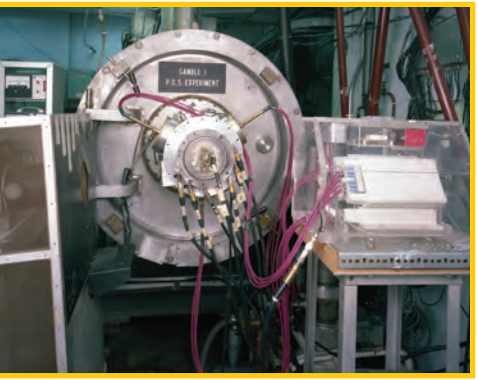
NRL has made significant contributions to the field of hydrogen fuel cells and to their application as high-energy-density sources for unmanned systems. Fuel cells electrochemically convert hydrogen fuel and oxygen in air into electricity and water. NRL has also played a critical role in developing novel electrocatalysts for hydrogen fuel cells and methods for their operation in sulfur-rich environments that would otherwise result in catastrophic poisoning. In parallel with these fundamental studies, NRL enabled the first successful flight of a fuel-cell-powered unmanned aerial vehicle (UAV).

Based on the UAV's flight time of over three hours, NRL began in 2006 to develop a concept for a submarine-launched unmanned aerial vehicle, the XFC, to be powered by a fuel cell that provides over six hours' endurance. A hydrogen fuel cell was key to the XFC mission, as a battery-powered vehicle would lack sufficient energy for acceptable endurance, and a combustion-engine-powered vehicle would create an unacceptable signature and would be difficult to launch from a torpedo tube. The XFC is on track for use by the U.S. Navy.

NRL pushed the envelope on the endurance achieved with fuel-cell-powered small UAVs. With the ONR-funded Ion Tiger research vehicle, NRL demonstrated a 26-hour flight using compressed hydrogen fuel in 2009 and then a 48-hour flight using cryogenic hydrogen in 2013. Both are unofficial world records for endurance. NRL has developed its own fuel-cell system to support Group 1 and 2 UAVs (up to ~100 lbs), which has been demonstrated in commercial UAVs and is being licensed by a U.S. industrial partner. NRL has also teamed with General Motors since 2010 to demonstrate that automotive hydrogen fuel cells can be effectively used for air-independent propulsion of a large, unmanned, undersea vehicle.

IMPACT: NRL created a new energy source for propulsion for UAVs, the hydrogen fuel cell, which is capable of both long endurance and low signature. These are benefits not provided by the limited endurance of batteries or the acoustic footprint of combustion engines. Fuel cells provide a path to long endurance missions for unmanned systems because of the high energy of hydrogen in combination with the high efficiency of the electrochemical fuel cell. As technology moves to electric propulsion, due to its higher reliability and efficiency, the Navy is well poised to develop this clean, stealthy technology for its next-generation systems.

HIGH-POWER, HIGH-CURRENT, PULSED-POWER GENERATORS



In the 1960s, high-power, pulsed-power research was driven by the need to produce intense sources of radiation in the laboratory to simulate the effects of nuclear weapons on commercial and military systems. The U.K. and the U.S. were exploring ways to generate 1 MA at 1 MV for 50 ns (5×10^{-8} s). NRL had pioneered the use of water as a dielectric in a lower-power, low-voltage water capacitor used to drive an exploding wire; then, ten years later, in 1968, NRL designed and built the Gamble I pulsed-power generator (750 kV, 500 kA, 50 ns). This was the first high-power, low-impedance facility to use demineralized water as a dielectric-energy-storage medium at high voltage. The advantages of water as a capacitive-energy-storage medium are that it has a high dielectric constant, is self-healing to electrical breakdowns, and acts as a good insulator for high-voltage pulses of 10^{-5} s duration or less. J. Martin and I. Smith in England performed water-breakdown measurements in 1965 that provided the critical design data for Gamble I.

The success of Gamble I led NRL to build the Gamble II generator that was, when completed in 1970, the largest pulsed-power generator of its kind in the world, capable of delivering 1 MV across a 1-ohm load for 50 ns. The 1 TW output power was more than the entire electrical power capacity of the U.S. At that time, the primary purpose for this capability was to provide an intense radiation source for simulating nuclear-weapon effects in the laboratory to supplement the U.S. underground-simulation-effects testing program. Military electronics were exposed to this radiation to assess their survivability in a real nuclear environment. Gamble III is being constructed now, with initial operations planned in 2026.

IMPACT: Gamble I and II were the prototypes for all modern high-power, low-impedance generators now in use in industrial laboratories, universities, DoD and DoE laboratories, and foreign laboratories. In addition to being critical for important weapon-effects simulations, pulsed-power technology based on water-dielectric capacitive energy storage has also generated other areas of research on high-power electron and ion beams and soft X-rays from z-pinch plasmas for inertial confinement fusion, matter at high-energy densities, directed-energy weapons, high-power microwaves, flash X-ray radiography, pumping gas lasers, and X-ray laser technology.

EXCIMER LASER TECHNOLOGY

NRL researchers S. Searles and G. Hart discovered the first excimer laser in 1975. Excimer lasers operate in the ultraviolet (UV) and have short-duration pulses that allow the study of fast processes. UV lasers can be more tightly focused relative to lasers with longer wavelengths in the visible range of the spectrum, and excimer lasers are more efficient than other UV lasers.

The demonstration at NRL that an electrical discharge could be used to make an excimer laser with order-of-magnitude-lower voltages led to commercial development. Once the commercial sector began development of the technology, excimer lasers became research tools for fundamental studies that increased rapidly in all fields, especially in biology and medicine. By 1998, over 10,000 articles had been published with "excimer laser" as a keyword. In the commercial sector, the technology was developed for photolithography in the semiconductor industry and for medical applications. Searles, Hart, and four others were presented the 1992 Rank Prize for Optoelectronics "for their discoveries leading to the development of the rare gas halide excimer lasers." The award read:

"Today's high power ultraviolet gas lasers find applications in science, industry, and medicine ranging from the production of integrated circuit chips by photolithographic techniques to a surgical procedure in which the cornea of the eye can be reshaped so as to correct for defects in vision."

Follow-on research at NRL led to the development of krypton-fluoride (KrF) excimer-laser technology for inertial confinement fusion (ICF) applications. The Laboratory's laser fusion program is the world leader in high-energy excimer-laser technology. Recently, NRL converted its Electra krypton-fluoride (KrF) laser system to argon-fluoride (ArF) operation, which has the potential to be a superior laser driver for ICF and inertial fusion energy due to its short wavelength, broad bandwidth, and high efficiency.

IMPACT: NRL's discovery of the excimer laser provided the research community with a new tool, especially for fundamental studies in biology and medicine. In the commercial sector, the laser found applications in the production of integrated circuit chips and in corneal sculpting for vision correction. In the latter application alone, the market was estimated to be over a billion dollars by the late 1990s. As for NRL's laser fusion program, the Electra ArF laser recently set a new energy record of 200 J. ArF laser light provides a larger ablation pressure for imploding a laser fusion target than any other laser technology.

FIRST OPERATIONAL SHIPBOARD LASER WEAPON

Challenges posed by asymmetric warfare and hypersonic missiles are placing new demands on the U.S. 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 weapon, the Laser Weapon System (LaWS).

The incoherent beam combining (IBC) concept that enabled LaWS was developed by NRL and Penn State University in 2006, eight years before the weapon system's deployment. The IBC concept provided a near-term path to a laser weapon and allowed the Navy to be the first service to field an operational laser weapon. NRL pioneered the use of single-mode fiber lasers with very good optical beam quality to extend the effective range of incoherently combined lasers. NRL carried out a proof-of-concept demonstration from 2007 to 2008 at the Naval Surface Warfare Center - Dahlgren Division and Starfire Optical Range in New Mexico. LaWS was a solid-state fiber laser (SSFL) compact enough to be installed on ships as small as the LCS class. SSFLs are relatively low-maintenance, have a low operating cost, and place less demand on the ship's power supply. In addition, they are easier to cool, provide good beam quality, and can achieve up to 35% power output efficiency relative to the power provided to the system (higher-than-average efficiency compared to other lasers at the time).

In 2014, LaWS was installed aboard the USS *Ponce* (Afloat Forward Staging Base (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.

IMPACT: Each shot from the prototype laser costs 59 cents. In contrast, the Standard Missile-2, a common surface-to-air weapon, costs the Navy roughly $400,000 per missile. However the impact of LaWS extends well beyond cost. LaWS was considered effective against a range of threats including unmanned aerial vehicles, slow-moving helicopters, rigid-hull inflatable boats, fast patrol craft, and multiple small boats in swarm-attack formations. With lasers supplementing missiles and other shipboard weapons, ships will also be able to remain at sea longer. The success of the LaWS program has spurred several high-energy-laser development programs across the Department of the Navy.

IMPROVED AIRCRAFT CANOPY AND WINDOW MATERIALS

NRL's interest in aircraft windows originated with the blowout failures of combat aircraft canopies. These failures resulted from the inability of the canopy material to halt the propagation of cracks caused by impacts of sharp objects or by missile penetration. In 1953, J. Kies applied NRL's pioneering research in fracture mechanics for the first time to a practical problem — the failure of combat aircraft canopies.

Experiments by I. Wolock, then at the National Bureau of Standards and later with NRL, showed that craze cracking of acrylic could be eliminated by hot stretching, a result that led Kies to the idea that hot stretching could add to the toughness of aircraft windows. Kies worked with commercial manufacturers of acrylic material (e.g., Rohm and Haas) and used fracture mechanics to ascertain the toughness of the material. In the course of the work, NRL shattered hundreds of aircraft canopies by projectile impact, and then carefully reassembled them to allow crack paths to be traced. Kies pointed out that the critical stress for a given crack size depended only on the product G_cE, which could be directly computed from the applied stress and crack size for the test.

The response of aircraft engineers concerned with testing stretch-toughened glazing materials was to express their fracture test results in values they termed K (K for Kies). Kies's work is also incorporated in design criteria for aircraft plastic glazing materials issued jointly by the Department of Commerce, the Department of the Navy, and the Department of the Air Force.

IMPACT: NRL worked cooperatively with the Air Force and with commercial manufacturers to introduce stretched acrylic plastic for military canopies with increased toughness, reduced weight, and prolonged service life. This material is now employed in military and civilian aircraft, thereby reducing a once-significant source of fatal accidents.

PURPLE-K-POWDER

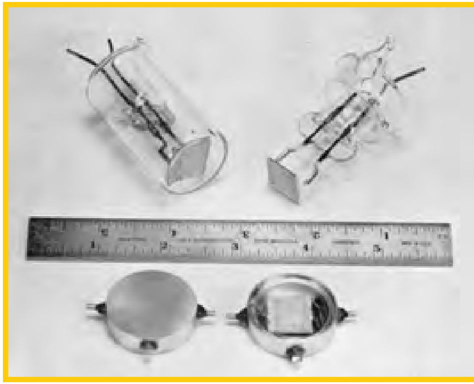
Prior to the development of potassium bicarbonate dry chemical extinguishing agent, or "Purple-K-Powder" (PKP), hydrocarbon fires were extinguished using either sodium bicarbonate dry chemical powder or protein foam. The dry chemical was effective on three-dimensional and "hidden" fires (e.g., debris from an aircraft crash), but provided no protection against reflash. Protein foams were used to extinguish fuel-spill or in-depth liquid pool fires. The thick, foam blanket provided reflash protection by excluding oxygen from the fuel surface, but foams were ineffective on 3D and hidden fires. The agents could not be used in combination because the foam bubbles were chemically attacked and destroyed by commercially available dry chemicals. The first step in developing an optimum approach was to develop a superior, foam-compatible dry chemical.

In 1959, a series of investigations by NRL in the area of chemical flame extinction gave birth to Purple-K-Powder. Powdered bicarbonate of soda as a flame-halting agent had been employed for many years, but its action had never been satisfactorily explained. Working with other investigators, NRL conducted fire tests with many powdered substances, which helped to clarify the chemical actions involved. This work came 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. This meant PKP extinguished a fuel fire in half the time or extinguished twice as much fire as before. Ensuing industry efforts resulted in production of surface coatings that allowed PKP to be compatible with foams.

IMPACT: The development of Purple-K-Powder represented a major advancement in the state of the art for flammable liquid fire protection. PKP became used throughout the Navy and in U.S. municipal and industrial fire protection operations, and thereafter throughout the world.

RADIATION DETECTION

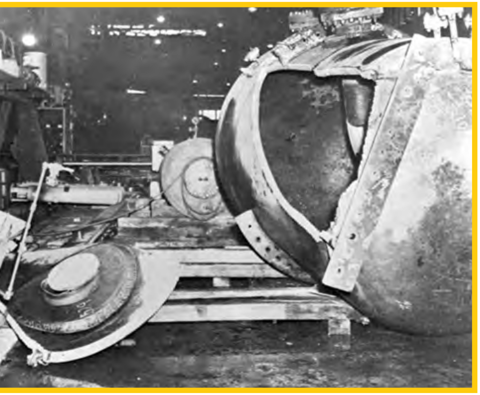
The need for accurate and convenient dosimetry was recognized soon after the discovery of ionizing radiation. NRL's J.H. Schulman developed a radiophotoluminescent glass dosimeter in 1951. This dosimeter, the DT-60/PD, was accepted as a standard radiation monitor in the 1950s. Later, in the 1960s, Schulman and his colleagues developed a successful thermoluminescent dosimeter. Until NRL's thermoluminescent dosimeter, no such device had been considered a suitable replacement for the photographic film badge for health physics monitoring. Although the film badge was capable in accurately detecting a lower level of radiation, it was an uneconomical and inconvenient method that prevented rapid estimations of dose. NRL's dosimeter satisfied the detection range necessary without the disadvantages of the film badge.



Following the September 11, 2001, terror attacks, NRL developed the Mobile Imaging and Spectroscopic Threat Identification (MISTI) system, a sensitive mobile gamma-ray spectroscopy system constructed and sent to Lawrence Berkeley National Laboratory for use in detailed background gamma-ray surveys. MISTI's success led to the development of a second-generation system at NRL known as SuperMISTI, funded by the Office of Naval Research (ONR) and constructed in 2009. In 2012, SuperMISTI was one of eight instruments fielded on a barge in an ONR-sponsored test. SuperMISTI detected and identified sources in all scenarios. Because of its sensitivity and mobility, SuperMISTI was later employed by the DoD and the wider government community in research programs with applicability in terrestrial and maritime domains.

IMPACT: During the 1950s, the Navy and the U.S. Air Force purchased several million of the NRL originated dosimeters for personnel monitoring in case of nuclear attack. NRL's radiation dosimeters were used to provide the military with an effective, convenient, and economical diagnostic tool for radiation exposure. They also served medical uses in areas such as clinical radiology and cancer treatment. The SuperMISTI system is a deployable asset of the Navy/DoD that has probed the limits of the possible with respect to standoff radiation detection, imaging, and localization. Passive detection and imaging of radioactive sources have been demonstrated on water at standoff distances of 300 feet.

NUCLEAR REACTOR SAFETY



A major application of NRL's fracture-test technology was the Laboratory's participation in the Heavy-Section Steel Technology Program conducted by the Nuclear Regulatory Commission. The technical issue was to determine the safety of nuclear reactor pressure vessels fabricated from 12-inch-thick steel as a function of the thickness and temperatures. NRL's W.S. Pellini and F.J. Loss built the apparatus and conducted experiments on full-thickness specimens to demonstrate the safety of the vessels. The program lasted several years and attracted international attention. The ASME Code rules for the operation of nuclear pressure vessels are based on the results of that program.

In the early 1960s, NRL demonstrated the potentially severe embrittlement of nuclear reactor steels to be a function of neutron exposure and irradiation (service) temperatures. While emphasizing light-water reactor pressure-containment steels and their modes of failure after neutron exposure, the properties of other reactor-component alloys were studied as well. Broad interest in NRL's work led to support by the Atomic Energy Commission and the Army.

This work is believed by most nuclear safety authorities to be a primary basis for assurance against catastrophic failure of radiation containment. In 1975, a definitive book by NRL's L.E. Steele, *Neutron Irradiation Embrittlement of Reactor Pressure Vessel Steels*, was published and became a landmark guide for specialists worldwide.

IMPACT: All military and civilian power reactors that feature a steel pressure shell are designed or operated, or both, on the fracture principles developed by NRL. In addition, the Laboratory's work in radiation embrittlement in reactor pressure vessel steels led to the production of radiation-resistant steels, which are applied in new reactors throughout the world, and in the assurance of reactor containment safety in older reactors.

MARINE SURFACE MONOLAYERS

Beginning in the early 1960s, NRL performed research on the nature and effects of surface-active substances at critical interfaces in the marine environment. Much of this early basic research was guided by W. Zisman. This research led to three applications:

Oil Spill Control — NRL discovered that certain invisibly thin surface films applied around oil spilled on water could compress the oil into a much smaller area and maintain the oil in a thick layer, thereby enhancing the efficiency of oil-recovery operations. While developing the technique, NRL worked with JBF Scientific Corp., a manufacturer of oil-recovery vessels. Following EPA approval, the method was incorporated into Navy pollution-control programs for harbors and bays. It has also been used in commercial training for oil-spill control.

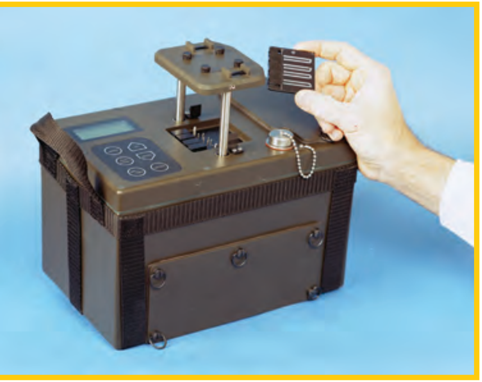
Seamarker — Used in combination with the standard green dye, NRL's surface-active compound spontaneously spreads rapidly over the sea surface and makes a much larger mark than the dye alone. Because of the damping effect of the compound on small capillary waves on the sea surface, the one-molecule-thick films are readily detectable both visually and by radar, with radar providing nighttime and poor-weather detectability.

Mosquito Control — NRL developed a thin surface film that prevents mosquitoes 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, not 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, nontoxic compound has been licensed for application [NRL-LIC-96-016] and has been used in mosquito-control districts across the U.S.

IMPACT: The mosquito-control technique has reduced public health hazards by controlling mosquitoes using a more environmentally safe method in place of toxins. The oil-spill-control technique has reduced damage to property, the fishing industry, and the environment. The sea marker benefits the military in air-sea-rescue operations.

OPTICAL IMMUNOASSAYS AND SENSORS

Beginning in the 1990s, NRL worked to develop portable biosensors intended to be easy to use and to require only that the sample be a relatively nonviscous liquid. Ideally, these biosensors would be sensitive and simple to use and would require minimal sample processing. The biosensors developed by NRL enabled applications from environmental monitoring of contaminants to food safety and clinical detection approaches. The developed systems used antibodies and other biomolecules to recognize biological threat agents and environmental hazards/contaminants rapidly and at extremely low concentrations.



NRL's Fiber Optic Biosensor (FOB) and the similar Continuous Flow Sensor were used for monitoring of explosives in groundwater and soil. The FOB and the Array-Based Biosensor were used to measure biological toxins in river water and clinical samples (blood, serum, plasma) and harmless bacteria released in field exercises and collected from the air. The Continuous Flow Sensor was utilized in the detection of drugs of abuse in urine and saliva. The Array-Based Biosensor was applied extensively to evaluation of contaminants in food and food-related products as well as the detection of biothreat agents.

The Continuous Flow Sensor informed manufacture of the Research International (RI) FAST 2000, applied by the Environmental Protection Agency in monitoring Superfund cleanup sites, and the Lifepoint, Inc. IMPACT Test System, applied to on-site lab-quality drug and alcohol testing. The RI Analyte 2000 provided capabilities for detection of both explosives-related contamination and biothreat agents. RI also developed and marketed the RAPTOR fiber-optic biosensor based on NRL's technology, a device that was embedded with the U.S. Marine Corps. The Array-Based Biosensor informed development of a system by Hanson Technologies for food safety, by Constellation Technology Corp. for biothreat detection in post offices, and by Precision Photonics for a clinical application. These systems have been tested extensively in field trials and demonstrated results that were comparable to sophisticated laboratory analytical techniques.

IMPACT: NRL's portable biosensors provide automated, sensitive detection of biological threats, drugs, and explosives in scenarios that include clinical applications, environmental monitoring, and food safety.

SURFACE ACOUSTIC WAVE CHEMICAL SENSORS

NRL pioneered the use of surface acoustic wave (SAW) technology to detect chemical vapors including chemical warfare agents (CWA). The Laboratory's efforts, dating back to 1981, were supported in the developmental stages by the U.S Army and the U.S. Air Force, and became a fielded technology when the DoD's Joint Chemical Agent Detector (JCAD) entered into low-rate production in 2007. Ultimately, the JCAD system based on SAW sensor devices was superseded by a handheld ion mobility spectrometry (IMS) technology. In a joint project, NRL partnered with the Army Edgewood Chemical Biological Center to develop a combined SAW and IMS chemical detector as a payload for an unmanned aerial vehicle.

Much of NRL's SAW R&D focused on developing chemically selective sorbent coatings for an array of devices to provide chemical selectivity, to amplify the signal response to hazardous chemistries, and to provide patterned signal responses to allow pattern-recognition-algorithm methods for CWA identification. In the early 1990s, NRL developed the first portable instrument to include a 4-SAW sensor array for patterned responses and a preconcentrator to provide increased sensitivity and analyte separations for improved system selectivity. From 1993 to 1995, an NRL-developed SAW sensor system was field tested. In the late 1990s and early 2000s, an NRL-developed SAW sensor system was integrated into a miniature UAV for airborne applications.

IMPACT: SAW chemical sensors, like those implemented in JCAD, were a significant capability for military and homeland defense detection of chemical-warfare agents. Advanced prototype units of JCAD were deployed in Operation Iraqi Freedom, and commercial models of JCAD subsequently became available. The handheld device sounded an alarm if nerve agents such as sarin or blister agents such as mustard gas were present. An earlier NRL SAW sensor system was developed for and employed by the U.S. Marine Corps Chemical and Biological Incident Response Force at the 1996 Olympic Games.

CT-ANALYST®

NRL's CT-Analyst® system (Contaminant Transport Analyst system) is the first operational instantaneous emergency assessment system for airborne contaminants and weapons-of-mass-destruction (WMD) threats in cities. It is a product application that was made possible by many years of NRL's related work in basic fluid dynamics and atmospheric research.

CT-Analyst® takes full account of the effect of buildings on airflow and is faster and more accurate than other existing systems. It can run on a PC and automatically combines data from sensors and verbal reports to plot optimal evacuation routes through use of a new fluid-dynamics-solution methodology called dispersion nomografs. This new approach uses detailed 3D, high-resolution fluid simulations to generate a complete database for the wind flow over a city, with all buildings and trees included. The database is compressed into 18 tables, or dispersion nomografs, one for each of 18 wind directions over the city.

IMPACT: CT-Analyst® was deployed as the nation's crisis-management model and was used at the HazMat Reachback Center (HRC), hosted by NRL during the 2009 presidential inauguration under the auspices of the Secret Service and the National Medical Response Team. The HRC was designated to provide crisis and consequence assessment for the Washington, D.C., area in the event of an airborne contaminant release. Participants included the Federal Bureau of Investigation, D.C. fire and police personnel, Army and Marine chemical-incident-support teams, the Department of Homeland Security, and the Defense Threat Reduction Agency. CT-Analyst® has also been deployed in Los Angeles for the DHS Golden Phoenix exercise. At the 2013 inauguration, CT-Analyst® provided the capability for initial assessment of possible airborne contaminant threat to the NRL team working in the Scientific Reachback Center (SRC) at the FBI's All Hazards Center, the coordinating center for emergency responses. CT-Analyst® was used specifically because of its speed and accuracy in modeling plumes in complex, urban geometries and assessing any potential threat. The assessments provided by CT-Analyst® were available for review within a minute or two. CT-Analyst® also supported the 2017 and 2021 inaugurations. CT-Analyst® has supported security for several Super Bowls, the Academy Awards, and State of the Union events. It is deployed with federal emergency managers, police, and fire officials in Washington, D.C., Los Angeles, Boston, Chicago, Hamburg, Germany, and Oslo, Norway.

SILENT GUARDIAN: DNA MICROARRAY TECHNOLOGY

Concerned about biological threats in the weeks surrounding the 2005 presidential inauguration, the assistant secretary of defense for nuclear, chemical, and biological defense programs (ASD(NCB)), directed that the Air Force surgeon general (AF/SG) and NRL operationally demonstrate a breakthrough biosurveillance technology developed by NRL for the Air Force's Epidemic Outbreak Surveillance (EOS) project. The technology, the resequencing pathogen microarray (RPM), resulted from the progress made in long-term NRL basic research. RPM was a system that could identify up to 100 different pathogen species in a single test using genetic sequence and new bioinformatics algorithms. The ASD(NCB) directed that the biosurveillance capability become operational in December 2004 and process up to 10,000 samples from military medical facilities across the National Capitol Region through January 2005.

The combined Silent Guardian team, comprising NRL scientists, Navy reservists, and U.S. Air Force staff, moved from routine laboratory research to full operational capability in less than six weeks. In samples collected from the active-duty military population, the team identified a full spectrum of circulating respiratory pathogens, often at the level of strains or individual variants (e.g., influenza virus). Inactivated biothreat agents, spiked into blinded samples, were also detected. An operational throughput of 300 test results from patient samples within 24 hours was demonstrated.

IMPACT: The Silent Guardian demonstration used NRL technologies to provide broad-spectrum pathogen surveillance of the Washington, D.C., region during the weeks surrounding the 2005 presidential inauguration. Later results demonstrated identification of all pathogens at ≥98% as compared to a battery of gold-standard tests. The use of genetic sequences for broad-spectrum pathogen identification was a historical first, preceding the capabilities of "next-generation sequencing" technologies developed since 2005. Sample processing and bioinformatics algorithms developed during Silent Guardian remain in widespread use today. NRL transferred RPM technology to TessArae, LLC in 2007, for which NRL was awarded a Federal Technology Transition award. The commercial RPM was used by the Navy during the initial identification of pandemic H1N1 influenza in 2009 at the US-Mexico border, and was approved by the U.S. Food and Drug Administration for H1N1 influenza diagnosis. High-multiplex polymerase chain reaction target amplification developed in Silent Guardian is part of current and future DoD programs of record for genetic sequence-based pathogen identification.

PERSONAL PROTECTIVE EQUIPMENT AND INJURY BIOMECHANICS

QuadGard body armor — By 2005, nearly two-thirds of the wounds sustained by U.S. troops in Iraq and Afghanistan were to the extremities, with 6 percent of the wounded requiring amputations. Medical personnel reported that fragments about the size of a pencil eraser caused most of these wounds, typically from improvised explosive devices (IEDs). QuadGard was the result of a rapid-response program to protect soldiers and Marines from the severe limb injuries caused by IEDs. NRL led a government-university-industry team to develop flexible, lightweight tactical garments that provide blast protection to arms, shoulders, legs, hips, and buttocks. Weighing only 10 pounds, the body armor incorporated new ballistic materials and designs determined after exhaustive studies that balanced vulnerability to injury and amputation against factors such as weight, flexibility, and comfort.

GelMan head protection — NRL developed a system to test the effects of blasts or impacts on live brain cells within an anthropomorphic human head surrogate. The cells are contained within a sealed cell pack that allows the cells to be removed from the laboratory environment and tested under real conditions, such as during training courses with live blast events. The anthropomorphic head allows for the determination of the effect of protective headgear, such as helmets, on cell response to blast or impact. The cell cultures are primary mouse cortex neurons grown in a 3D collagen hydrogel to mimic their native environment. The GelMan-Head system consists of a plastic human skull mounted to a standard Hybrid III neck. The “brain” comprises two pieces. The rear section contains a pocket to hold the cell pack, while the front portion of the “brain” mimics the properties of grey matter. The skull/brain/cell pack system can be fitted with helmets or other protective gear.

IMPACT: QuadGard transitioned from concept to combat use in only 17 months and was immediately fielded by U.S. Marine units in Iraq, followed soon after by Navy Seabees. Additional sets were provided to the Army and the Air Force for test-and-evaluation purposes. The potential operational uses of the body armor include convoy crews, checkpoint duty, security operations, roadside patrols, explosive ordnance reconnaissance, and forward-deployed medical personnel. The GelMan system provided the first method for exposing brain cells to blast events under realistic conditions and represents a novel method of determining the mechanisms by which blast events can alter the biology of the brain. It also offers potential for a biological component to helmet performance testing.

TRANSPARENT ARMOR

DoD spends tens of millions of dollars, and thousands of hours each year, replacing failed ballistic glass on tactical vehicles such as the High Mobility Multipurpose Wheeled Vehicle (HMMWV), the Medium Tactical Vehicle Replacement (MTVR), and others. In the majority of cases, the glass, also called transparent armor (TA), has not been damaged but the spall layer has delaminated, allowing water or dirt to infiltrate, making it difficult to safely operate the vehicle. This failure mode occurs across all armored vehicle platforms. TA lifetime is typically 3–5 years and replacement costs are $1K–10K per window. A 2017 study of 1,000 Marine Corps vehicles showed that 60% of MTVRs and 70% of HMMWVs should have one or both windshields replaced to achieve full readiness.

From 2011 to 2013, NRL demonstrated the repair of TA at a fraction of the cost of a new part. These first studies demonstrated a range of repair methods, including both in-frame and out-of-frame as well as using a traditional autoclave or a radio-frequency press. The bond strength and durability of the relaminated parts was found to depend on the type of repair. Based on the success of that study, NRL continued to serve as the primary in-house technical expert for the Marine Corps's PEO Land Systems as the repair process has been refined and transitioned to industry partners. NRL supported final transition of the repair, serving as the subject-matter expert to oversee final demonstration and to develop the test plan. That test plan enabled the USMC chief engineer to sign a memo formally allowing relaminated TA as a source of TA acquisition.

NRL is continuing to drive TA lifetime research, currently leading the federal government's largest testing and evaluation of transparent armor, with participation by every domestic manufacturer of transparent armor. The data from this testing will enable prediction of transparent armor lifetime so that parts can be purchased on a cost-per-year of expected life. NRL is advising both USMC and Army program offices on TA lifetime.

IMPACT: NRL's partnership with the Marine Corps's PEO Land Systems has changed TA from a short-lived, costly consumable to a repairable item and has dramatically shifted the economics of transparent armor. The immediate effect of the repair technology will be to enable increased vehicle readiness by allowing units to replace degraded TA at a much lower cost. In 2018, NRL was recognized as part of a team that received the Navy Innovation Excellence Acquisition Team of the Year Award for developing a repair solution for delaminated TA, estimated to save the U.S. Marine Corps $105 million over a five-year period.

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