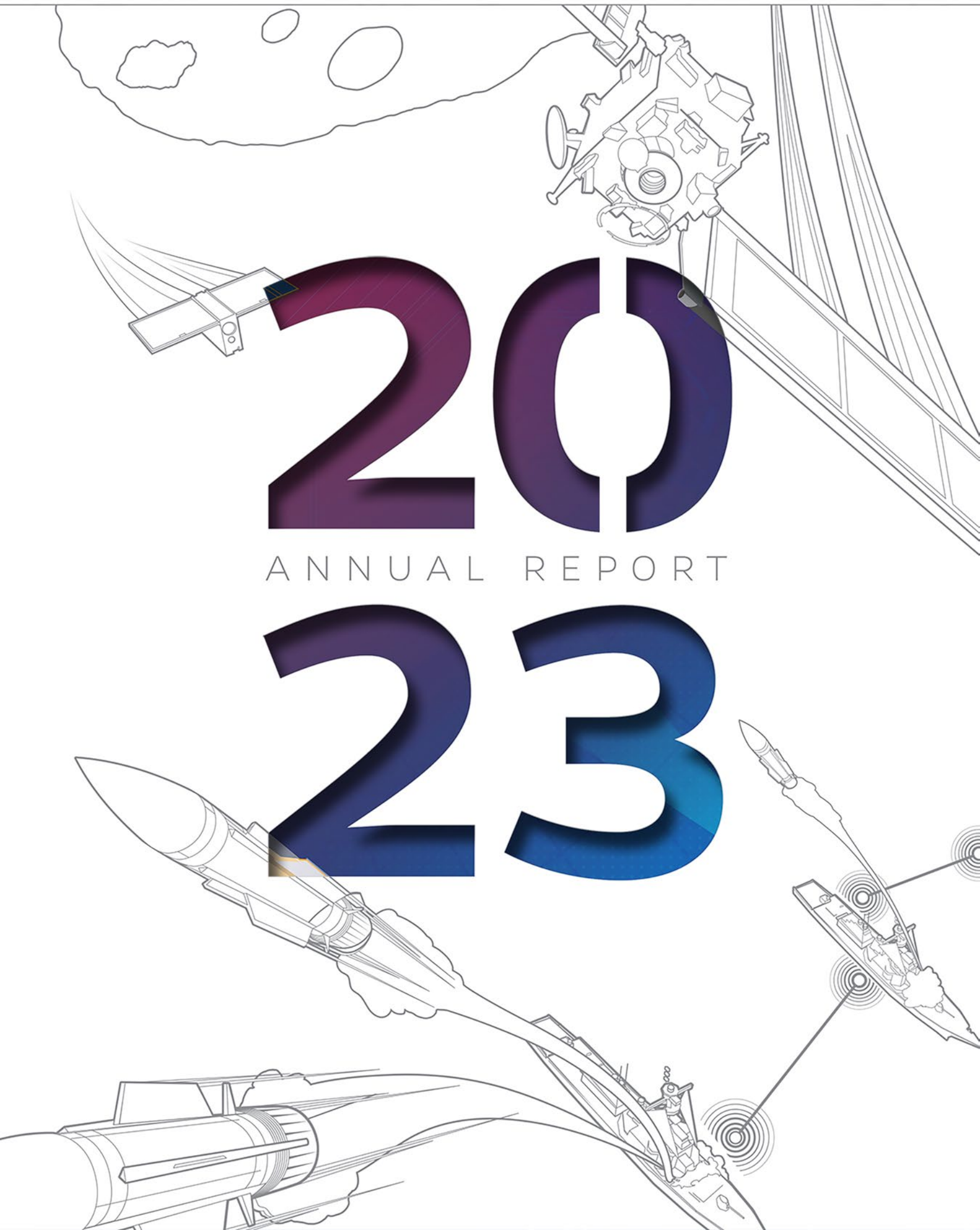
THE JOHNS HOPKINS APPLIED PHYSICS LABORATORY



# 2023 ANNUAL REPORT

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On March 15, at APL's first in-person All-Hands meeting since before the COVID pandemic, Director Ralph Semmel unveiled two new Defining Innovations to staff members: Ballistic Missile Defense From the Sea and Planetary Defense.



# DIRECTOR'S MESSAGE

For more than 80 years, the Applied Physics Laboratory has created and delivered game-changing innovations and critical contributions that have enhanced our nation's security and well-being. This past year, as we and our allies across the globe were confronted by increasingly complex and intense challenges, APL's contributions proved as vital as ever.

Ensuring our nation's role as the world's leader in science and technology requires a deep understanding of critical challenges, world-class expertise and a culture of collaborative innovation—all of which APL has rigorously developed and nurtured since its founding. A number of years ago, we began a process to identify those innovations, from among the thousands of operational capabilities we have provided to our sponsors, that have had the most profound impact. At the time, we selected nine Defining Innovations: paradigm-shifting breakthroughs that changed the course of history. Across the Laboratory, we highlighted the pivotal effects of these innovations—the proximity fuze, satellite navigation, and the Cooperative Engagement Capability (CEC), to name just three—and the staff members who persevered to bring them to life.

Earlier this year, as we concluded our 80th anniversary celebration, we announced two new Defining Innovations. The first, Ballistic Missile Defense From the Sea, proved that an existing ship-based missile defense system could be modified to protect against ballistic missiles, and essentially hit a bullet with a bullet, in space, from a moving vessel. The second, Planetary Defense, represented the culmination of years of scientific studies, simulations and exercises led by APL researchers, and resulted in the world's first successful planetary defense mission and kinetic impact demonstration.

In the following pages, you will read about some of our recent critical contributions in fields such as AI and autonomy, biomechanics, hypersonics, cybersecurity, materials science, climate and health security, and maritime technologies. These accomplishments were made possible by the dedicated and innovative staff members across all of APL's sectors and departments. While the outstanding work described in this annual report represents only a small percentage of the programs and projects we undertake at the Laboratory, it is indicative of the extraordinary impact we continue to have.

As always, I am incredibly proud of our staff members and their unwavering commitment to solving the complex challenges we tackle for our sponsors. Whether we are creating new technologies to counter the actions of hostile nations and rogue actors, unraveling the mysteries of our solar system or producing life-changing medical advances, I am inspired by the talent and focus of our people and the remarkable capabilities we deliver to our nation and the world.

Ralph Semmel

# DEFENDING THE NATION

Since its founding in 1942, APL has proudly served as a world-class research and development institution and has created some of the nation's most critical defense technologies. In that time, threats to our national security have continued to emerge and evolve, increasing in complexity and involving new operational environments and regimes. To meet these challenges and maintain the nation's defensive edge, APL calls upon its deep expertise in a number of technical domains, both cutting-edge and foundational, provided by the more than 8,700 staff members who collaborate in teams across the Lab.

Kiel Gordon, a cybersecurity software developer, is in APL's Live data, Integration, Validation, and Experimentation Lab, an immersive data processing facility that helps researchers stream and visualize data in real time.


The Live data, Integration, Validation and Experimentation (LIVE) Lab allows researchers to visualize data on information networks and use automated pattern recognition to discover anomalies that indicate cyberattacks and track the progress of diseases.

## New Mission Areas Rise to Meet Evolving Challenges and Strategies

In recent years, the United States has faced new threats to national security, as well as new opportunities to maintain its leadership in science and technology. In response to this evolving landscape and to meet these rising challenges, the Laboratory in October realigned several of its mission areas. The changes now position APL to continue delivering critical, game-changing innovations to our sponsors and the nation and closely align with the government's National Security Strategy.

With these changes, the Laboratory now has 13 mission areas overall. The Air and Missile Defense Sector now comprises Homeland Defense and Theater Defense; National Health, part of the Asymmetric Operations Sector, became Global Health to better reflect its refocused mission; and the Space Exploration Sector now includes Civil Space Flight and Space Formulation alongside National Security Space.

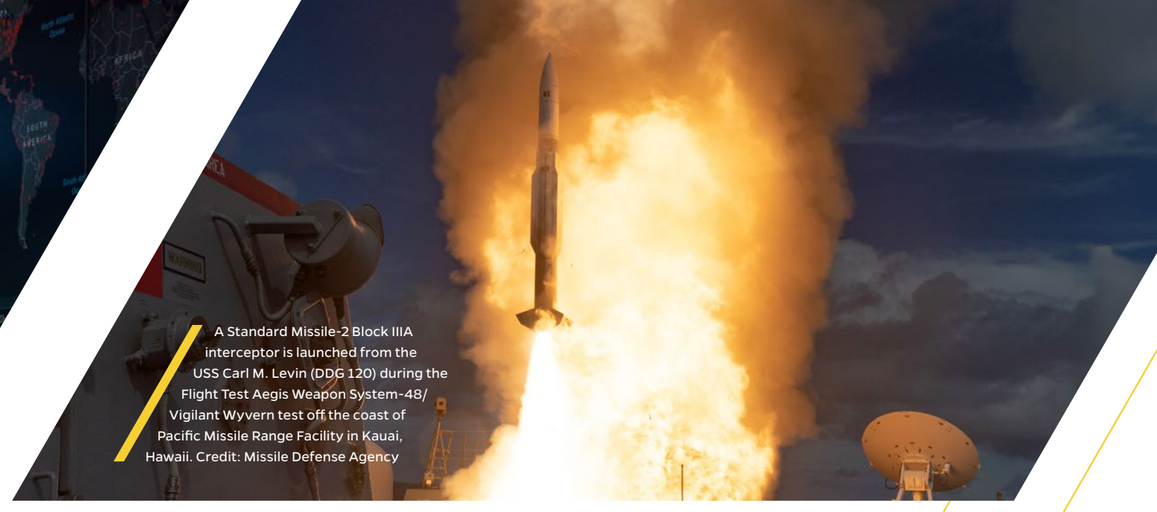
These new mission areas will focus on defending against new adversary capabilities that could threaten the homeland or forward theaters of operations; using science and engineering to counter natural and artificial health threats; and envisioning, building and delivering first-of-a-kind space capabilities for the nation.

"World events over the past few years have refocused our national strategy across many domains," said APL Director Ralph Semmel. "One of the great strengths of the Laboratory is our ability to encompass a wide range of expertise while remaining agile enough to maneuver to meet new threats and challenges. These new mission areas are already working on critical contributions for our sponsors and contributing to strategically critical programs."

### APL's 13 mission areas:

- Civil Space Flight
- Cyber Operations
- Global Health
- Homeland Defense
- National Security Analysis
- National Security Space
- Precision Strike
- Research & Exploratory Development
- Sea Control
- Space Formulation
- Special Operations
- Strategic Deterrence
- Theater Defense





A Standard Missile-2 Block IIIA interceptor is launched from the USS Carl M. Levin (DDG 120) during the Flight Test Aegis Weapon System-48/Vigilant Wyvern test off the coast of Pacific Missile Range Facility in Kauai, Hawaii. Credit: Missile Defense Agency

## Achieving Sea-Based Defense Milestones

In 2023, APL was integral to the achievement of multiple significant advances in Integrated Air and Missile Defense (IAMD).

In October, U.S. Navy Arleigh Burke-class destroyer USS Carl M. Levin (DDG 120) successfully intercepted multiple targets in an IAMD test executed by the U.S. Navy Program Executive Office Integrated Warfare Systems (PEO IWS) and the Missile Defense Agency (MDA), with significant contributions from APL, from the Pacific Missile Range Facility in Hawaii.

The joint test, Flight Test Aegis Weapon System-48 (FTM-48)/Vigilant Wyvern, demonstrated the capability of a ballistic missile defense (BMD)-configured Aegis ship to detect, track, engage and execute intercepts of two short-range ballistic missile targets, while concurrently demonstrating an anti-air warfare (AAW) engagement of two subsonic anti-ship cruise missile drone targets.

The realistic, live-fire raid scenario represented one of the largest IAMD events ever conducted in the U.S. Indo-Pacific Command Area of Responsibility and demonstrated for the first time a concurrent BMD and AAW raid.

"The proliferation of ballistic and cruise missile technology across the globe has served to magnify the importance of IAMD capabilities for the U. S. Navy," said APL Theater Defense Mission Area Executive Vishal Giare. "This successful test demonstrates the robustness of integrated missile defense technologies at sea today."

The APL team was instrumental in the FTM-48 scenario test definition, modeling of the test target parameters, preflight weapon system performance assessment, flight test execution and postflight assessment of flight test objectives. As the technical direction agent to both the Aegis BMD and PEO IWS, APL is integral in the full systems engineering life cycle, including testing and transition of capability to the U.S. and allied fleet forces. The success of this test demonstrated the operational capability to U.S. and allied fleet forces, as well as those who might seek to do the nation harm.

"The success of Vigilant Wyvern is a huge milestone," said Rear Adm. Seiko Okano, Program Executive Officer Integrated Warfare Systems. "This test event is the first of its kind and an excellent example of collaboration between organizations, further progressing a unified mission to increase capability."

That same month, on Oct. 7, the first Aegis Flight III Arleigh Burke destroyer (USS Jack H. Lucas, DDG 125) was commissioned with the AN/SPY-6(V)1 Air and Missile Defense Radar (AMDR) — a game-changing system that began as an APL concept, which the Laboratory then worked with industry partners and the Navy to fully realize.

The SPY-6(V)1 is a four-face, electronically steered phased-array radar that supports multimission warfare operations. SPY-6(V)1 integrates into an upgraded version of the Aegis combat system and provides defense against advanced air, ballistic and hypersonic threats in complex manmade and natural environments.

AMDR delivers the Navy's first true IAMD radar capability that was purpose-built for simultaneous air and missile defense, and it allows a single combatant to detect, track and engage previously unattainable raid sizes to improve carrier strike group survivability. APL was instrumental in developing and testing these IAMD capabilities. SPY-6(V)1 will begin at-sea developmental testing in 2024, and scaled variants of the

radar will be integrated and deployed on additional surface combatants over the next 10 years—ushering in a new generation of surface Navy capabilities.

In addition, APL is working with MDA and the Navy to deploy a multiunit, multimission prototype planning system called Cerberus to Navy ships and ashore facilities via the Overmatch Software Armory (OSA). OSA is a development, security and operations (DevSecOps) platform for developing, testing, staging, integrating and deploying applications hosted by the Naval Information Warfare Center Pacific.

In 2023, the Cerberus team pioneered efforts to implement an end-to-end DevSecOps process within Project Overmatch's government-provided environments and stage an updated Cerberus version on a classified network.

This classified-accessible version of Cerberus has showcased how a centrally managed planning resource can help the larger planning community access, review and revise plans in real time. This capability also enables unprecedented levels of rapid collaboration between members of the planning community, including APL, the Naval Surface and Mine Warfighting Development Center (NSMWDC) and MDA, on tasks like screening questions from the fleet and combatant commands on urgent real-world operations.

Finally, In cooperation with MDA and the Navy, APL also supported Flight Test Aegis Weapon System 31 Event 1a (FTM-31 E1a). The test successfully demonstrated the capability of a BMD-configured Aegis ship to detect, track, engage and intercept a medium-range ballistic missile (MRBM) target in the terminal phase of flight using the SM-6 Dual II with Software Upgrade (SWUP) in a single salvo of two interceptors. FTM-31 E1a was the third successful flight test of an Aegis BMD-equipped vessel using the SM-6 Dual II missile and the first Aegis Baseline 9.C2.0 (BMD 5.1) intercept of an MRBM target using the SM-6 Dual II SWUP missile. FTM-31 E1a highlights adjustments made after FTM-31 E1, conducted in May 2021, which only met some of its objectives.

A medium-range ballistic missile target is launched from the Pacific Missile Range Facility in Kauai, Hawaii, as part of the Missile Defense Agency's Flight Test Aegis Weapon System 31 Event 1a (FTM-31 E1a), held on March 30, 2023, in cooperation with the U.S. Navy. Credit: Missile Defense Agency

The successful execution of this mission validates that the upgraded SM-6 Dual II SWUP capability is now ready for use by the warfighter to defend and protect our allies and deployed forces worldwide.

"This was an incredible accomplishment and key milestone for the sea-based defense program," said former MDA Director Vice Adm. Jon Hill, U.S. Navy (Ret.), in the MDA FTM-31 E1a press release. "This test proved our capabilities in an operationally realistic scenario, which is a critical step in increasing our capability to outpace emerging threats."

The APL team was an integral part of the FTM-31 E1a scenario test definition, test target parameter modeling, high-fidelity weapon system model development, preflight weapon system performance assessment, flight test execution and postflight assessment of the test objectives. As the technical direction agent for Aegis BMD, and as with FTM-48, APL plays a key part in the full systems engineering life cycle, including testing and transition of BMD capability to U.S. and allied fleet forces.

> **"This test proved our capabilities in an operationally realistic scenario, which is a critical step in increasing our capability to outpace emerging threats."**
>
> — **Vice Adm. Jon Hill,** U.S. Navy (Ret.), Former Missile Defense Agency Director

# Defending U.S. Interests and Allies Overseas

APL is focused on assurance of our allies in Europe, and in 2023, a team of analysts supported the U.S. Army Europe and Africa's 21st Theater Sustainment Command (TSC) in its response to the conflict in Ukraine.

The team surveyed and collected data during time-constrained mobilization of U.S. units that used Army Prepositioned Stock (APS) located throughout the theater. APS is Army equipment stored and maintained in strategic and global locations for use in crisis or conflict operations.

Typically, exercises are planned years in advance and the organizations participating have plenty of time to prepare. This response included mobilization of thousands of troops and pieces of equipment, giving analysts an opportunity to highlight a range of valuable lessons for the 21st TSC staff.

This real-world analysis provided a better understanding of operational timelines and requirements for potential contingency operations in the future, and it was crucial in developing key findings and recommendations for the 21st TSC. This work continued APL's support of the 21st TSC—the U.S. Army Europe and Africa's lead organization for all sustainment missions in those regions.


Equipment from an Army worksite in Dülmen, Germany, is prepared for inventory at Tapa Barracks, Estonia. Credit: U.S. Army

The USS Shoup, shown here on another mission, was one of several ships used to test fire the Evolved Sea Sparrow Missile Block 2. Credit: U.S. Navy

## Setting Technical Direction

As technical direction agent for the Navy's Evolved Seasparrow Missile Block 2 program, APL is providing guidance on a system designed to provide ships with short-range self-defense against aircraft and anti-ship cruise missiles. Credit: U.S. Navy

As the technical direction agent (TDA) for multiple programs, APL works with the government to define the programs' direction, evaluate technical risks, and develop solutions to critical challenges. The Laboratory also works with industry partners to ensure technical success of the product development.

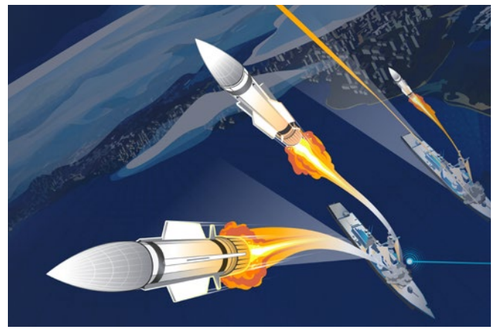
In 2023, recognizing APL's contributions to the design, development, integration, testing and fielding of the Evolved Seasparrow Missile (ESSM), the Navy assigned APL as the TDA of the ESSM Block 2 and future ESSM development program. The latest variant of ESSM, the Block 2 is designed to provide ships with short-range self-defense against aircraft and anti-ship missiles. Its major upgrade is a dual-mode seeker, which allows the missile to home in on targets in the absence of radar illumination. APL will work with Raytheon and government laboratories to ensure the successful deployment of ESSM Block 2 and development of future upgrades.

APL was also named TDA for the Navy's hypersonic Conventional Prompt Strike (CPS) system, a weapon system concept the Lab has worked on for 14 years. APL defined the technical baseline for CPS, which consists of a launcher, missile, glide body and weapon control system. CPS will be the nation's first available hypersonic strike capability when fielded as the Army's Long-Range Hypersonic Weapon.

In March, the Navy Maritime Surveillance Systems program office also named APL the TDA for the Deployable Surveillance System. APL brings a breadth of passive and active sonar expertise — along with extensive testing and operational experience — to this program and has been a part of the development and oversight of rapidly deployable acoustic systems for wide-area ocean surveillance since 2016, leading development of a growing range of deployable systems.

These TDA designations continue in part because of APL's years of technical expertise and profound understanding of naval operations. APL has served as the TDA for several Navy systems since the 1970s — beginning with responsibility as Standard Missile TDA and expanding into Aegis and Aegis Ballistic Missile Defense (BMD) TDA designations in the 1990s and 2000s. As TDA, APL plays an integral role in the full systems engineering life cycle, including testing and transition of capability to the fleet. It was that leadership that, in part, led to BMD From the Sea being named the Laboratory's 10th Defining Innovation in March 2023.

In the mid-1990s, APL responded to the critical challenge of proliferating ballistic missile threats, leading the development of the transformational system needed to demonstrate BMD From the Sea. The resulting experiments proved that BMD technology could be integrated with a Navy weapon system to "hit a bullet with a bullet" in space from the sea. APL's critical contributions opened the door for the Navy's role in BMD. The resulting impact is felt far beyond our nation's shores as BMD now provides enduring defense at sea and ashore across the globe.



APL's leadership of the Aegis Ballistic Missile Defense system was an integral part of what made Ballistic Missile Defense From the Sea an APL Defining Innovation. For more on the two additions made in 2023 to APL's Defining Innovations, see page 40.

# Decades of Undersea Commitment and Readiness for the Road Ahead

Since its inception, APL has been making critical technology, analysis, strategy and policy contributions to the nation's defense at sea.

For the majority of that time — the past six decades — APL experts have produced integral, detailed analyses and performance estimates to inform senior decision-makers on the effectiveness of the U.S. submarine-launched ballistic missile segment of the nation's nuclear deterrence triad.

Strategic Deterrence Mission Area Executive Steve Lewia at the event celebrating 60 years of Planning Factors reports with current and past team members as well as dignitaries from the U.S. Strategic Command, the U.S. Navy, and the U.K. government and Royal Navy.

In these annual "Planning Factors" reports, an 80-person APL team analyzes and explains evolving capabilities to provide objective, critical information to U.S. Navy Strategic Systems Programs in support of the Navy's Fleet Ballistic Missile program. Decision-makers in the Navy and at the highest levels of the government use these reports for strategic planning.

To mark the Laboratory's 60th year as an independent evaluator for this critical information, the Strategic Deterrence Mission Area hosted a celebration in June for current and past Planning Factors team members as well as dignitaries from the U.S. Strategic Command, the U.S. Navy, and the U.K. government and Royal Navy.

Just before that seminal celebration, in May, more than 600 members of the U.S. Submarine Force, industry, laboratories, academia, warfare centers, and acquisition and intelligence communities gathered at APL's Kossiakoff Center for the 35th annual Submarine Technology Symposium (STS). The three-day event, organized by APL and the Naval Submarine League, centered on the theme "Undersea Dominance and Deterrence in the Decade of Maximum Danger."

The Ohio-class ballistic missile submarine USS Louisiana (SSBN 743) transits Puget Sound following a 41-month engineered refueling overhaul at Puget Sound Naval Shipyard and Intermediate Maintenance Facility in 2023. Credit: U.S. Navy

The focus on the next 10 years was inspired by national and international events. While the U.S. continues to have the most capable undersea forces in the world, its adversaries — particularly China and Russia — are expending resources in an attempt to erode that advantage in this domain. The 2024 symposium included a special panel devoted to enhancing U.S. alliances and partnerships. Navy submarine leaders from Australia, the U.K. and the U.S. (AUKUS) held a joint discussion on working together to keep our adversaries at bay.

From left, Cdre. Tom Phillips, Royal Australian Navy, director, General Submarines (Australia); Cdre. Andy Perks, Royal Navy, deputy director, Underwater Battlespace Capability (U.K.); and Martin Irvine, executive director, Submarine Forces (U.S.), participate in a panel discussion at the 35th annual Submarine Technology Symposium.

The nation is moving quickly to modernize the fleet, maintain its edge and enhance its relationship with allies in this critical decade and beyond. The U.S. submarine community is united around maintaining a sense of urgency in order to execute plans, preserve asymmetric advantage and ensure the nation is ready to fight — now.

"If there is one community that can align quickly and come together rapidly to tackle a seemingly unsurmountable challenge, it is this one," said Lisa Blodgett, head of APL's Force Projection Sector.

APL is helping the Navy develop standards for the software used to operate uncrewed surface and undersea vehicles.

# Leveraging Autonomy for National Defense

APL is helping the Navy leap ahead in the specification, development and fielding of software and artificial intelligence (AI) for autonomous uncrewed surface vehicles (USVs).

On behalf of the service's Unmanned Maritime Systems program office, APL is helping define the Unmanned Maritime Autonomy Architecture (UMAA), a set of interface standards to modularize autonomy behaviors, perception and situational awareness, navigation, and mission management software into reusable chunks.

UMAA is part of the Navy's efforts to modernize its acquisition cycle. APL has also developed the initial software conforming to UMAA specifications — software that not only proves the validity of the UMAA approach but also serves as the government-owned USV software baseline that can easily be expanded and improved in the future. The modular nature of UMAA allows for the rapid insertion of autonomy components into USVs. In particular, APL's Mission Management autonomy software enables USVs to make complex decisions to accomplish competing mission objectives in dynamic environments without the need for human interaction.

In the past year, APL has installed its USV autonomy and perception software on Laboratory- and contractor-owned small boats. The vessels have been tested in Navy demonstrations and experiments in the Chesapeake Bay; near Key West, Florida; off the California coast; in the North Carolina and Virginia portions of the Intercoastal Waterway; and in the Atlantic Ocean near Colombia, South America.

In other areas, APL is focusing on achieving autonomous behavior through trusted processes or algorithms, and rigorous testing is integral to the success of autonomous systems in military applications.

Understanding that, in 2023, APL began equipping AFWERX — a technology directorate of the Air Force Research Laboratory (AFRL) and the innovation arm of the Department of the Air Force — with capabilities to quickly and safely test novel autonomy and AI on small uncrewed vehicles in complex, interactive environments.

The work is part of AFWERX's new Autonomy Prime program, which is focused on a rapid autonomy testing "proving ground," which seeks to accelerate affordable and iterative testing of autonomy in aircraft.

**"With APL's autonomy expertise and long history as a partner to the government, we are well positioned to help AFWERX innovate at a pace that matches the rapid growth of autonomy technologies."**

— **Chris Eaton,** Aerospace and Systems Engineer and APL's Project Manager for TACE

The APL-developed TACE, which stands for Safe Testing of Autonomy in Complex, Interactive Environments, will sit between a vehicle's safety-critical control system and its autonomy and mission systems. TACE monitors commands sent from the autonomy system to the autopilot and passes information such as the vehicle's position, speed and orientation as well as sensor and mission environment data back to the autonomy.

Its runtime assurance capability keeps systems under test from violating predefined constraints. If there is a failure or violation of safety constraints, TACE will take control of the vehicle from the autonomy and return it to safety. TACE also provides a ground station capability allowing the operator to monitor and manage the systems under test.

The APL team will also leverage a decade of experience with prior TACE programs to build out LVC (live, virtual and constructive) environments, which enable preflight simulation of missions without jeopardizing the aircraft. Autonomy and AI software developers can quickly test their algorithms and then move rapidly and with confidence to a live vehicle.

Additionally, the APL team will develop a modular, high-performance computing environment to integrate TACE and autonomy processing onto multiple autonomous vehicles. The APL team is also developing an integration environment to allow offline and online development and integration of autonomous solutions for rapid transition from software to a live flight test. As Autonomy Prime advances, APL will continue to develop technology and capabilities for new mission sets and vehicles.

The team behind the APL-developed TACE, which stands for Safe Testing of Autonomy in Complex, Interactive Environments, developed a high-performance computing environment to integrate TACE onto multiple autonomous vehicles.

An illustration of NASA astronauts at the lunar South Pole. Home to the world's largest community of lunar experts in a single location, APL is a leader in cislunar security. Credit: NASA

# Space: Where Science and Security Intersect

APL is applying its expertise in lunar science and technology to a Defense Advanced Research Projects Agency (DARPA) initiative to identify and propose interoperating standards for commercial infrastructure on the Moon.

In 2023, APL was named to manage and provide technical leadership for the Lunar Operating Guidelines for Infrastructure Consortium (LOGIC), through which DARPA aims to convene stakeholders across industry, academia and government to identify critical lunar infrastructure interoperability and interface needs. Where appropriate, LOGIC will encourage the community to develop operational guidelines and pathways to close interoperability gaps.

Working closely with NASA's Lunar Surface Innovation Initiative (LSII) and Lunar Surface Innovation Consortium (LSIC), LOGIC seeks to accelerate the development of consensus-driven interoperability standards in areas such as power distribution; communications; positioning, navigation and timing (PNT); lunar surface surveying; and cislunar space traffic control. APL operates LSIC and LSII in collaboration with NASA's Space Technology Mission Directorate. Hundreds of universities and businesses are participating in NASA's Artemis lunar exploration program through this consortium.

> **"Whether for scientific, security or economic objectives, development of cislunar technology has long been a focus at APL. We are excited to apply our team's capabilities for the benefit of our nation."**
>
> **— Bobby Braun,** Space Exploration Sector Head


Barbara Golf, the United States Space Force Strategic Advisor for Space Domain Awareness, delivers a keynote during the 2023 Cislunar Security Conference at APL.

A panel discussion at the 2023 Cislunar Security Conference, a forum on implications of ensuring free access to, transit to and use of the Earth–Moon system beyond geosynchronous orbit.

"We are proud to support DARPA and NASA in achieving their integrated goals in the cislunar domain," said Bobby Braun, head of APL's Space Exploration Sector. Cislunar space is the region of the Earth–Moon system beyond Earth's geosynchronous orbit. "Whether for scientific, security or economic objectives, development of cislunar technology has long been a focus at APL. We are excited to apply our team's capabilities for the benefit of our nation."

DARPA recently initiated its 10-Year Lunar Architecture (LunA-10) capability study, looking to spur the development of a civil lunar framework for peaceful U.S. and international use. It seeks to rapidly develop foundational technology concepts that move away from individual efforts and toward a series of shareable, scalable systems that interoperate and create monetizable services for future lunar users.

DARPA and NASA are working closely together to leverage the expertise of the LSII and LSIC communities and bring decades of operational experience to bear. Through LOGIC, APL will facilitate working groups focused on the benefits of standardization and modular components, assess the impact of potential technologies on the broader space community and develop community-recommended solution paths to close interoperability gaps.

And as military and economic potential in space continues to grow, APL is at the forefront of efforts to secure the U.S. advantage in this increasingly critical domain. The Laboratory held its fourth annual Cislunar Security Conference in December — a forum on the technology, policy, doctrine and strategy implications of ensuring free access to, transit to and use of cislunar space.

Home to the world's largest community of lunar experts in a single location, APL is a leader in cislunar security. In the 2024 fiscal year, which runs Oct. 1, 2023, through Sept. 30, 2024, the Lab is strategically focused on defining an architecture to provide secure, robust communications and PNT for cislunar assets and activities.

The Cislunar Security Conference started in 2020 and has quickly grown into the largest conference in the country dedicated to cislunar security, providing a forum for hundreds of experts around the country to collaborate and discuss needs (as well as potential solutions) related to securing the cislunar region and the lunar surface in the future.

A group of U.S. Space Force staff and the incoming inaugural cohort of Schriever and West Space Scholars toured APL in July as a part of the Space Force's Professional Military Education (PME) program, a new partnership between the Space Force and Johns Hopkins University (JHU) Nitze School of Advanced International Studies.

# BOLD INNOVATION

In a world teeming with increasingly difficult challenges, APL researchers are developing cutting-edge solutions that will make our planet safer and more secure. From innovative manufacturing to resilient cybersecurity technologies and revolutionary advancements that utilize the power of artificial intelligence for materials discovery and health care, the Laboratory is pushing the boundaries of the possible and turning bold ideas into reality.

An APL-developed thermoelectric device to restore cold sensation in amputees' phantom limbs has been recognized by R&D World magazine as one of the world's most revolutionary technologies.

**This advancement, one of the first of its kind,** enables a new capability for improved prostheses, haptics and a variety of other applications.

Longtime collaborator Johnny Matheny

> **“We spend years in the lab, and to see our technology have an impact on someone’s quality of life is incredibly satisfying.”**
>
> — **Rama Venkatasubramanian,** Semiconductor Device Engineer and Chief Technologist for APL’s Thermoelectrics Research

## A Cool Touch: Restoring Cold Sensation in Amputees’ Phantom Limbs

Building on more than a decade of revolutionary prosthetics work, Laboratory researchers used an APL-developed thermoelectric device to restore cold sensation in amputees’ phantom limbs. This advancement, one of the first of its kind, enables a new capability for a variety of research and industrial applications, including improved prostheses, haptics for new modalities in augmented reality, thermally modulated pain management, cooling electronics and lasers, and energy harvesting in satellites. The device was recognized as one of the top 100 revolutionary technologies in the world with a 2023 R&D 100 Award from R&D World magazine in the IT/Electrical category.

Development of the thermoelectric cooling device, known as the thin-film thermoelectric cooling device (TFTEC), began in 2016 when Rama Venkatasubramanian, a semiconductor device engineer and chief technologist for APL’s thermoelectrics research, began developing nanoengineered materials and devices for the Defense Advanced Research Projects Agency Materials for Transduction (MATRIX) program. To support MATRIX, APL developed materials that enabled an entirely new set of transduction capabilities for several Department of Defense applications, including cooling computer chips and engine components.

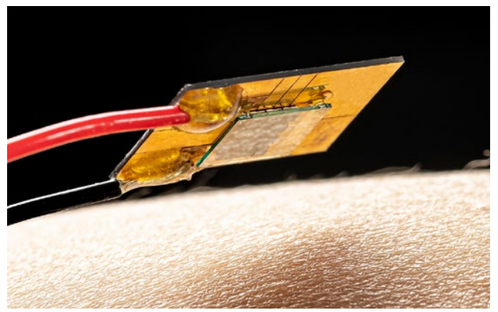
The advancements were so significant that by the end of 2019, Bobby Armiger, who supervises APL’s Exploratory Science Branch, wondered if the devices could facilitate temperature sensation in phantom limbs of amputees. With support from the Uniformed Services University of the Health Sciences, he teamed up with neuroengineer Luke Osborn and a broader team of neuroscientists, roboticists and thermoelectrics engineers to create a wearable device that responds quickly enough and with enough intensity to match the human body’s ability to rapidly sense temperature changes.

The TFTEC, no thicker than a credit card and lighter than a few drops of water, is one of the world’s smallest, fastest and most powerful refrigeration devices. After the team developed the TFTEC, they also developed a wearable version, able to provide intense cooling in less than a second for human perception for prostheses and haptics.

To test the TFTEC’s efficacy, researchers mapped thermal sensations in the phantom hands of four amputees by using noninvasive nerve stimulation. In this method, researchers place electrodes on different parts of an amputee’s upper arm, where nerves from the residual limb have regrown. They can then stimulate sensation — typically pressure, but in this case temperature.

The TFTEC elicited cooling sensations for all four test participants during a cold-detection task, whereas traditional thermoelectric technology did so for only half of them — and the TFTEC did it eight times faster and with three times the intensity while using half the energy.

“We spend years in the lab, and to see our technology have an impact on someone’s quality of life is incredibly satisfying,” Venkatasubramanian said.



APL researchers developed one of the world’s smallest and fastest refrigeration devices, as thin as a credit card and lighter than a few drops of water.

APL engineers are creating wearable devices that match the human body’s ability to rapidly sense temperature changes.

# Quantum Biology: The Key to Unlocking Understanding of Magnetosensitivity

Using quantum mechanics, APL engineers, physicists, biologists and chemists collaborated with international colleagues to better understand one of nature's biggest mysteries: magnetosensitivity, which is an organism's ability to sense Earth's magnetic field and use it as a tool to adjust its own biological processes.

Some of the results were surprising.

Several APL researchers teamed up with Ilia Solov'yov, a physicist from the Carl von Ossietzky University of Oldenburg, to find that an enzyme central to human metabolism shares some key features with a magnetically sensitive protein found in birds.

The human protein look-alike is the electron transfer flavoprotein (ETF), an enzyme in mitochondria responsible for transferring electrons to generate the energy that keeps us alive. ETF isn't known to be magnetically sensitive in humans, but its structure and ability to produce reactive oxygen species (ROS) are remarkably similar to certain cryptochrome proteins that are known to be magnetosensitive in birds and other species.

If they know how ROS are generated inside an enzyme, the researchers could, theoretically, control their magnetic field response. However, although team members were able to experimentally measure the levels of ROS formed by ETF, they could not see where the reactive species were forming within the enzyme.

Enter computational modeling. By running molecular dynamic simulations to model oxygen diffusion in ETF enzymes, the team isolated where oxygen most likely binds to ETF and in turn discovered several high-probability locations where ROS were likely being made.

"From there, we can go back and possibly engineer the ETF and see how we're able to increase or decrease the output of those reactions," said Janna Domenico, a computational chemist. Doing so could give researchers the ability to modulate the extent of the protein's magnetic field response inside a person's cells.

This budding research has a vast array of possible applications, such as studies that could shed light on how certain metabolic disorders arise from ETF mutations or even on how an astronaut's brain cells would respond to the extraterrestrial magnetic fields on the Moon or Mars.

"This game-changing research opens up the possibility that an external magnetic field could influence the underlying chemistry of a protein found in humans," said Carlos Martino, a research engineer.

Researchers found that an enzyme central to human metabolism shares some key features with a magnetically sensitive protein found in birds.

> **"This game-changing research opens up the possibility that an external magnetic field could influence the underlying chemistry of a protein found in humans."**
>
> — **Carlos Martino,** Research Engineer

Nam Le, Janna Domenico and colleagues are using computer modeling to better understand magnetosensitivity, the ability to sense Earth's magnetic field and use it to adjust some biological processes.

> “By carefully prompting a single large language model to respond fluidly, we can realize the impact well-trained conversational AI could have in combat care situations.”
>
> — **Sam Barham,** Computer Scientist and CPG-AI Team Lead

## Lifesaving Technology for the Battlefield and Beyond

In battle, soldiers with no specialized medical knowledge may find themselves offering prolonged care to injured comrades. Naturally, they will need all the help they can get.

By applying knowledge gleaned from established care procedures, APL developed a proof of concept for a conversational artificial intelligence (AI) agent that can provide basic medical guidance in plain language. The project, known as Clinical Practice Guideline-driven AI (CPG-AI), is based on a large language model (LLM). LLMs, such as ChatGPT, were well covered by the news media in 2023. One way APL is applying the technology is to this critical challenge.

Methods of providing clinical support using AI tend to be highly structured — requiring precisely calibrated rules and meticulously labeled training data — and better suited for providing alerts and reminders to experts in a relatively calm environment. But coaching untrained novices (or even trained medics) in a chaotic environment is a different story.

Traditionally, custom neural networks would have to be trained on every individual task. LLMs, on the other hand, are trained on vast amounts of unlabeled data — text, in this case — and not specialized for any particular task. That means an LLM can theoretically adapt to any situation that can be described in words using text prompts that provide the situational context and relevant information.

“LLMs have this incredible ability to adapt to virtually any task in the realm of natural language,” said Sam Barham, a computer scientist and lead of the CPG-AI team, which also includes Arun Reddy, Michael Kelbaugh and Caitlyn Bishop. “So instead of training multiple neural networks on multiple capabilities, you can carefully prompt a single LLM to respond fluidly to a situation.”

Until recently, LLMs were far too slow and required too much computing power to be useful in such an operational context. However, recent advances in computing power and in LLMs themselves have made the prospect feasible. CPG-AI draws on a wider APL-developed software ecosystem for developing apps that take advantage of LLMs. This ecosystem is known internally as RALF, or Reconfigurable APL Language Model Framework. RALF was developed in APL’s Intelligent Systems Center as part of an internally funded strategic initiative.

To further structure the underlying LLM’s reasoning and improve its ability to accurately select text and medical advice, Barham and team developed a novel mechanism that gives access to the Tactical Combat Casualty Care (TCCC) guidelines, a set of procedures developed by the Department of Defense Joint Trauma System to help relative novices provide trauma care on the battlefield. Conveniently, the TCCC guidelines exist as flowcharts that easily translate into a machine-readable form.

In addition, the researchers found and converted to text more than 30 clinical practice guidelines from the Joint Trauma System, including guidelines for treating burns, blunt trauma and other common battlefield conditions.

In the project’s first phase, the team produced a prototype that can infer a patient’s condition from conversational input, answer questions accurately and without jargon, and guide the user through tactical field care — a category that encompasses common battlefield injuries such as burns and bleeding.

Boosted by RALF capabilities, CPG-AI can also switch smoothly between stepping through a care instruction and answering a user’s questions.

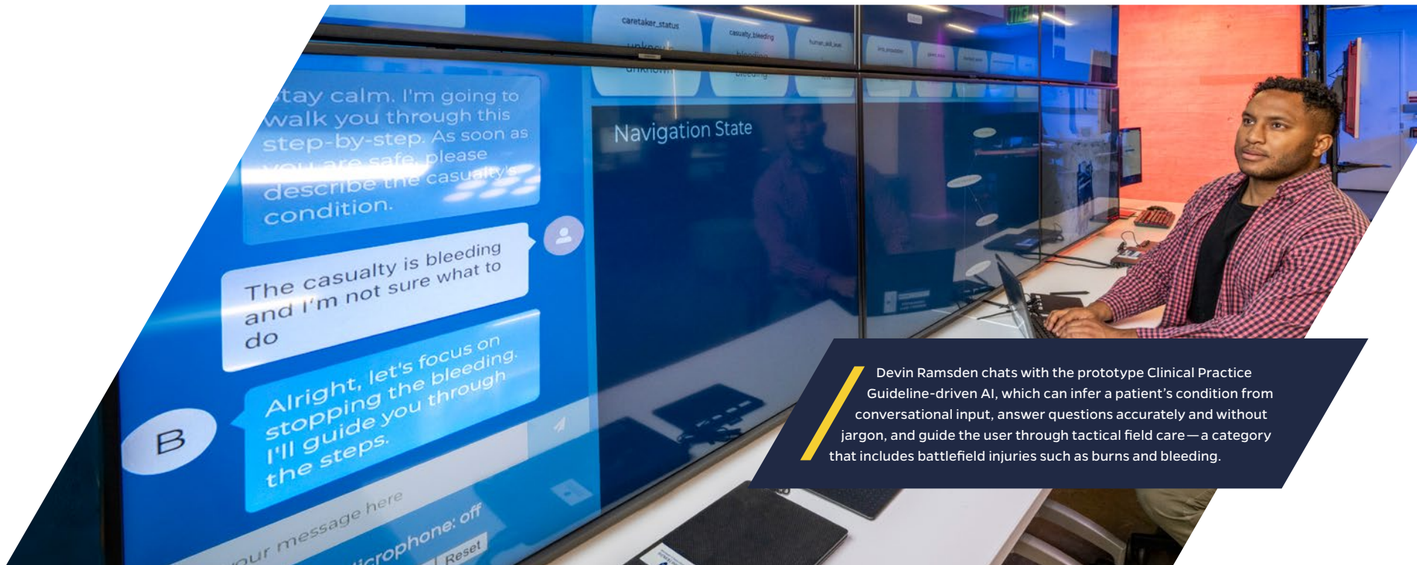
There are plenty of battlefield injuries, however, that necessitate more than an AI assistant to handle. Subdural hematomas — bleeding on the brain — occur in about one-third of fatal traumatic brain injuries among U.S. warfighters and civilians. At home, most subdural hematoma sufferers are rushed to a hospital, where a neurosurgeon can relieve the pressure on the brain through a variety of methods. But on the battlefield, warfighters lack the means to even diagnose, let alone treat, these life-threatening injuries.

Tackling this challenge head-on, APL researchers have developed groundbreaking technology to enable military medics to both diagnose and treat subdural hematomas in the austere environment of the battlefield.

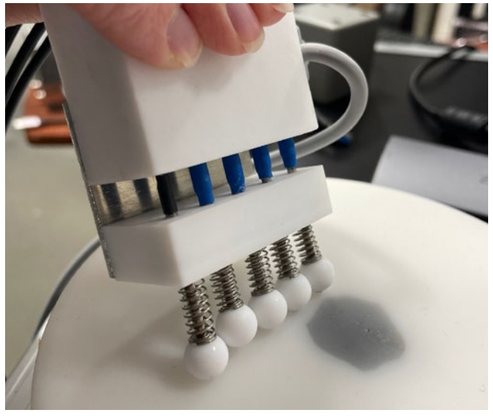
It starts with a detection tool that packs the capabilities analogous to much larger units (such as computed tomography scans, commonly known as CT scans, which require massive pieces of equipment) into a device that fits in a field medic’s bag.

Through efforts to realize a high-fidelity, noninvasive brain–computer interface, APL researchers discovered that diffuse optical imaging — which sends near-infrared light through the skull into the brain and detects changes in light absorption and scatter caused by changes in blood flow — could detect subdural hematomas.

Currently, a cap with dozens of optical fibers is fitted over a patient’s head. Half of the fibers deliver light into the brain, and half detect the light that is scattered through the tissue. The device is too large and complex for field medics to carry, so the team is working to reduce its size to a handheld unit that uses only four optical fibers. It will ultimately resemble an ultrasound wand or a scanner that could be slowly moved across the scalp.




Devin Ramsden chats with the prototype Clinical Practice Guideline-driven AI, which can infer a patient’s condition from conversational input, answer questions accurately and without jargon, and guide the user through tactical field care — a category that includes battlefield injuries such as burns and bleeding.



A prototype of the subdural hematoma detection device, outfitted with sensors that can accurately identify hematomas from scalp lacerations and other shallow bleeds.

The device is outfitted with sensors that can accurately identify hematomas from scalp lacerations and other shallow bleeds outside the skull. The team also used new technology to increase the device's sensitivity to faint infrared light signals — helpful because extravascular blood, or hemorrhaged blood, absorbs more near-infrared light than nonruptured blood. Setting it further apart from current methods, APL's detection device also uses what is called frequency domain diffuse optics to identify a hemorrhage. This technique enables the device to measure the absolute optical absorption value of the tissue, localizing the center of the hemorrhage rather than just detecting whether one is present like other similar devices do.

Beyond providing a method of diagnosis, the APL team set out to create a device that could treat brain bleeds by extracting liquid or clotted blood from a hemorrhage. The device would need to easily, quickly and consistently access the hematoma; relieve the pressure on the patient's brain; seal the area to maintain sterility; and stay in place for up to 72 hours — and be small enough for battlefield use.

After the instruments undergo a successful round of testing, the team plans additional tests to refine the instruments — potentially combining the detection and drilling devices. Beyond the battlefield, the technology could be useful in any remote environment, and the detection device alone could even be used to prioritize where brain injury patients need to go when they get to a hospital.

In related work, APL researchers are using machine learning techniques to improve systems for treating spinal cord injuries.

Spinal cord epidural stimulation (scES) technology, which passes electrical current directly to the injured area, is already used to treat pain. But key technology gaps — mainly in the software that controls how scES hardware delivers that stimulation — have hindered the method's potential to alleviate limitations in sensory and motor function, the autonomic nervous system and other functions impacted by spinal cord injury.

**"We've been testing our algorithm against the decisions made by clinicians. So far, our algorithm is matching what clinicians do."**

— **Bree Christie,** Neuroprosthetics Research Scientist

APL is developing systems to address those gaps.

Accurately targeting a spinal cord implant (like an scES device) is a huge challenge. The industry standard for visualizing the inside of the body involves looking at 3D anatomy through annotated 2D image slices, which lack the user-friendly, spatially intuitive perspective that would be useful to clinicians and surgeons who implant these devices. Led by engineer Jordan Matelsky, the APL team developed a pathway for converting that 2D imagery into a more natural 3D visualization that's easy to comprehend and quick to navigate.

Once an scES device is implanted, the level of stimulation delivered to the spinal cord area must be carefully controlled, but it must also respond dynamically to changes — both short-term ones, like shifts in the user's posture, and long-term ones, such as neural adaptations in the user's brain and body.

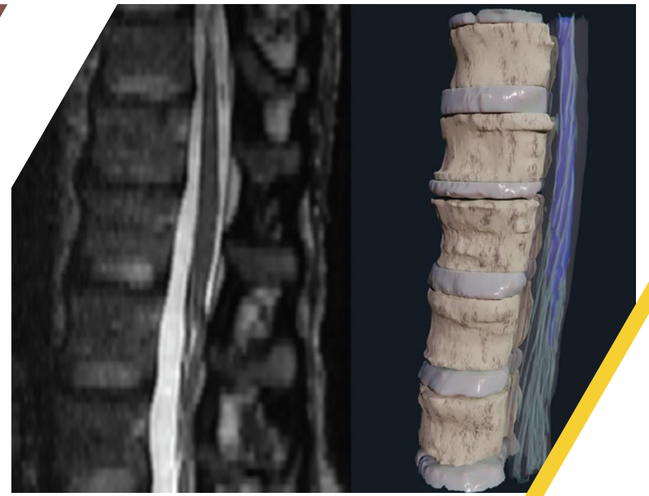
Using training data from clinicians at the University of Louisville in Kentucky and working with medical device manufacturer Medtronic, neuroprosthetics research scientist Bree Christie and team developed algorithms that can modulate the stimulation patients receive.

"We've been taking simple datasets and testing our algorithm against the decisions made by clinicians," Christie said. "So far our algorithm is matching what clinicians do — which is a good start."

The APL team plans to gradually incorporate more stimulation parameters into the algorithm to increase the level of complexity it can handle and to apply machine learning techniques to make it more robust against physical disturbances that patients encounter in the real world.

**"The device will be almost like an ultrasound wand, or something you can slowly move across the scalp and scan for hematomas."**

— **Carissa Rodriguez,** Optical Scientist



An APL team developed a pipeline for converting 2D MRI imagery (left) into 3D visualizations (right) to assist surgeons in placing implants that help restore motor control to people with spinal cord injuries.

The amphibious assault ship USS Bataan (LHD 5) sails in the Arabian Gulf. With APL technology and guidance, sailors onboard 3D-printed a sprayer plate to repair the ship's ballasting system, which provides critical stability while the vessel is at sea. Credit: U.S. Navy/Mass Communication Specialist Seaman Apprentice Darren Newell

# Additive Impact at Home and in the Field

In 2023, sailors on the USS Bataan (LHD 5) used the first hybrid manufacturing system permanently installed onboard a U.S. naval surface ship to fabricate a component and deliver critical repairs while at sea. The part, a stainless steel sprayer plate used to repair one of the ship's de-ballasting air compressors, was made and installed in less than five days with support from Naval Sea Systems Command's Technology Office (NAVSEA O5T) and APL engineers — turning the Navy's Afloat Additive Manufacturing concept into reality.

The sprayer plate, which disperses lubricating and cooling oil onto gears and bindings, was fully manufactured on the ship. With the air compressors repaired, the ship's ballasting system, which provides much-needed stability to the vessel, was operational once again, and the Bataan avoided a costly and inopportune return to port.

The NAVSEA-sponsored hybrid manufacturing system, which APL helped install aboard the Bataan in October 2022, features both directed energy deposition 3D-printing additive and traditional subtractive manufacturing capabilities, such as milling and drilling. When the sprayer plate broke and no spares were available onboard, sailors reached out to NAVSEA and APL to see whether the part could be manufactured using the newly installed machine.

Neither NAVSEA nor APL had yet developed the technical instructions for the printer to produce a sprayer plate. So ship engineers used computer-aided design software to produce a digital model of the part, which they sent to APL using the secure Digital Manufacturing Environment, a communication system that enables transmission of NAVSEA-developed technical data packages between ship and shore.

APL houses a printing system identical to the Bataan's, and senior mechanical fabrication technician Hunter Turco and mechanical engineer Drew Seker coordinated closely with mechanical engineer Bryan Kessel in NAVSEA's Naval Surface Warfare Center, Carderock Division, to create instructions to produce the part using only the tools that were available to the sailors aboard the ship.

With the successful production of the sprayer plate serving as a proof of concept, APL continues to work with the Navy to expand and improve the Digital Manufacturing Environment.

"APL is uniquely positioned to respond to this challenge because of the breadth of expertise at the Lab," said Ed Chapman, assistant manager of APL's Maritime Expeditionary Warfare Program Area. "Where one area of the Lab excels at understanding the Navy's needs and developing solutions to address them, others across APL have the technical expertise to make those solutions a reality."

Machinery Repairman 1st Class Cory Hover demonstrates the software used to design the sprayer plate, which was also fabricated aboard the Bataan by using additive manufacturing. Credit: U.S. Navy/Mass Communication Specialist 2nd Class Bradley Rickard


Drew Seker, Bryan Kessel and Hunter Turco were part of the team that helped sailors fabricate a stainless steel sprayer plate at sea. Kessel holds an identical replica of the sprayer plate that was fabricated at APL.

That breadth and depth of expertise holds true as APL delivers real-time improvements to additive manufacturing systems that are currently used in the field, while simultaneously providing cutting-edge research about new materials that could one day be deployed in extreme environments.

APL's rapid additive manufacturing materials development framework uses simulation and novel measurement techniques to dramatically condense the time it takes to generate optimal processing conditions for a new material — from months and years to days. The framework consists of four steps: computational fluid dynamics modeling, experiments and fabrication design, X-ray computed tomography and high-throughput testing.

From enabling complex metallic shapes that survive extreme temperatures to creating 4D shape-morphing components or producing materials that are nearly impossible to achieve with other types of manufacturing, the framework is being used extensively across the Laboratory.

In one project, APL researchers used the framework to identify processing parameters for generating corrosion-resistant steel, providing potential for enhancing corrosion resistance and thereby extending use of additively manufactured steel parts used in marine environments. In another, researchers relied on rapid materials development to discover the optimal performance of nickel titanium, a material that has long confounded additive manufacturers.

A new NASA Space Technology Research Institute, led by Carnegie Mellon University and the Johns Hopkins Whiting School of Engineering, will apply the APL process toward development of computational models and simulation tools for qualification and certification of additively manufactured spacecraft parts. This envisioned modeling tool set will be validated against experimental data, a process that will be accelerated using APL's framework.

"This capability changes how we can use additive manufacturing," said Steven Storck, a senior researcher who specializes in manufacturing science. "It's allowing us to set parameters for materials and complete numerous projects that would otherwise not be possible within tighter time frames."

> **"APL is uniquely positioned to respond to this challenge because of the breadth of expertise at the Lab."**
>
> — **Ed Chapman,** Assistant Program Area Manager for Maritime Expeditionary Warfare

# Accelerating the Pace of Discovery, Development and Testing of Advanced Materials

A multidisciplinary APL team discovered a novel superconductor using AI — a breakthrough enabled by blending expertise in materials science with real data to develop a predictive AI model, which vastly accelerates the timeline of targeted materials discovery.

Superconductors — materials that, when cooled below a critical temperature, can conduct electricity without losing energy — are used in many cutting-edge technologies. The new superconductor is an alloy of zirconium, indium and nickel with a superconducting transition temperature of around 9 degrees Kelvin. That its discovery took only three months, nearly three times faster than previously reported rates, clearly demonstrates the revolutionary potential of AI-enabled targeted discovery in materials science. After the initial discovery, the team completed a validation and testing period to confirm their findings.

The team worked on a project called MITHRIL — short for Material Invention Through Hypothesis-unbiased, Real-time, Interdisciplinary Learning — that draws on the combined expertise and creativity of materials researchers and computer scientists to discover materials in a targeted fashion. This work is done in close collaboration with the Johns Hopkins Krieger School of Arts and Sciences.

Why use AI? Just the sheer number of possible materials makes the discovery task almost inconceivably time-consuming for humans. And while both humans and computers reason from what is known, computers can be trained to systematically sample the unknown.

That unknown sampling capability is a big part of why the team chose superconductors as a test case — because so much is known about superconductors and their material composition, the team surmised the AI would be able to quickly identify and target untested compositions with high potential to be novel superconductors.

The team leveraged large, publicly available datasets of superconductors and other known materials to train its models. While useful, these datasets inevitably contain human biases because scientists tend to look for new superconductors by making small tweaks to existing ones rather than making big leaps that might lead to costly failures.

By using AI, it is possible to understand and compensate for the effects of human biases and to push the research where people haven't yet thought to look. And the combination of AI and human expertise shows promise in other areas of material and chemical discovery.

This multidisciplinary APL team, with expertise spanning materials science to computer science, rapidly accelerated the targeted materials discovery timeline.

> **"Often, materials are discovered by way of serendipitous accidents. That's a real problem for critically needed materials."**
>
> — **Christopher Stiles,** Senior Computational Materials Researcher

In fact, approaches similar to MITHRIL are being applied to the discovery of materials with desirable magnetic properties for energy production, as well as materials to enable more efficient battery technologies and high-strength, high-entropy alloys.

"We have this romantic notion that materials are discovered through diligent fundamental research, but it happens far more often by way of serendipitous accidents," said Christopher Stiles, a senior computational materials researcher. "That's a real problem for critically needed materials."

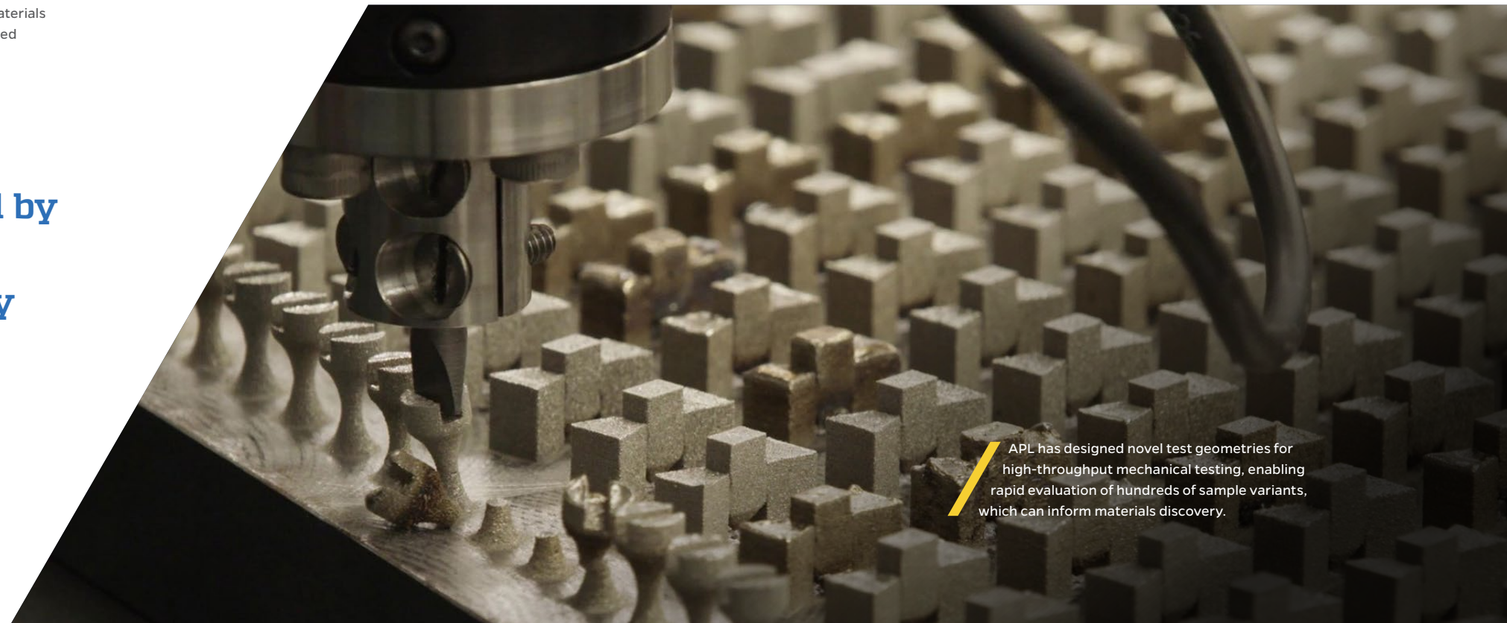
That issue, as it relates to integral materials, applies directly to efforts to mitigate climate change. More than half the energy consumed in American homes is spent on heating and cooling. And data centers — the buildings used to house critical computer systems and associated components, such as telecommunications and storage systems — spend more than 40% of their energy on thermal regulation for their electronics.

APL researchers have made a significant breakthrough in advanced materials that can efficiently manage thermal conditions, particularly in buildings and data centers, offering a promising solution that could lessen energy consumption and subsequent climate-related impacts.

Materials scientist Bella Hunt holds a wafer with a novel thermal coating technology developed at APL that enables advanced materials to efficiently manage thermal conditions in buildings and data centers.

The research focuses on adaptive, thin-film, tungsten-doped vanadium dioxide ($VO_2$) composites that can insulate heat when it is cool and radiate heat when it gets hot. $VO_2$ composites demonstrate a unique ability to transition from a low-temperature reflective state to a high-temperature emissive state at a specific threshold (around 68 degrees Celsius).

However, researchers have discovered that by "doping" $VO_2$ with high-valence tungsten, the transition temperature can be reduced to near room temperature (around 22 degrees Celsius), making it highly suitable for various thermal management applications.



APL has designed novel test geometries for high-throughput mechanical testing, enabling rapid evaluation of hundreds of sample variants, which can inform materials discovery.

An artist's rendering of APL's deep-sea lander, which allows researchers to test a variety of materials and equipment in real oceanic conditions.

> **"With the U.S. military's growing need for more undersea and seabed-based systems, there is a greater desire for more testing at depth."**
>
> — **Clara Smart,** Ocean Engineer

The research team designed and demonstrated a multilayer film composed of a metallic ground plane, an oxide dielectric spacer and a thin layer of tungsten-doped $VO_2$. Through a controlled fabrication process, the team deposited films with various thermal adaptive layer thicknesses and dopant levels. The results established that films with thinner thermal adaptive layers exhibited better performance in the metallic phase, maximizing the emissive contrast.

The research findings show great promise in revolutionizing thermal management technology. Moving forward, the team plans to continue to explore thinner doped-$VO_2$ layers and nano-patterned stacks to further optimize the material's performance.

And as more materials are discovered and created, testing them is pivotal, particularly in operational settings, like the deep sea.

The open ocean is rough on many types of materials, electronics and mechanical systems. This especially concerns the U.S. Navy, which operates everything from ships and submarines to a variety of sensors at sea across a range of depths.

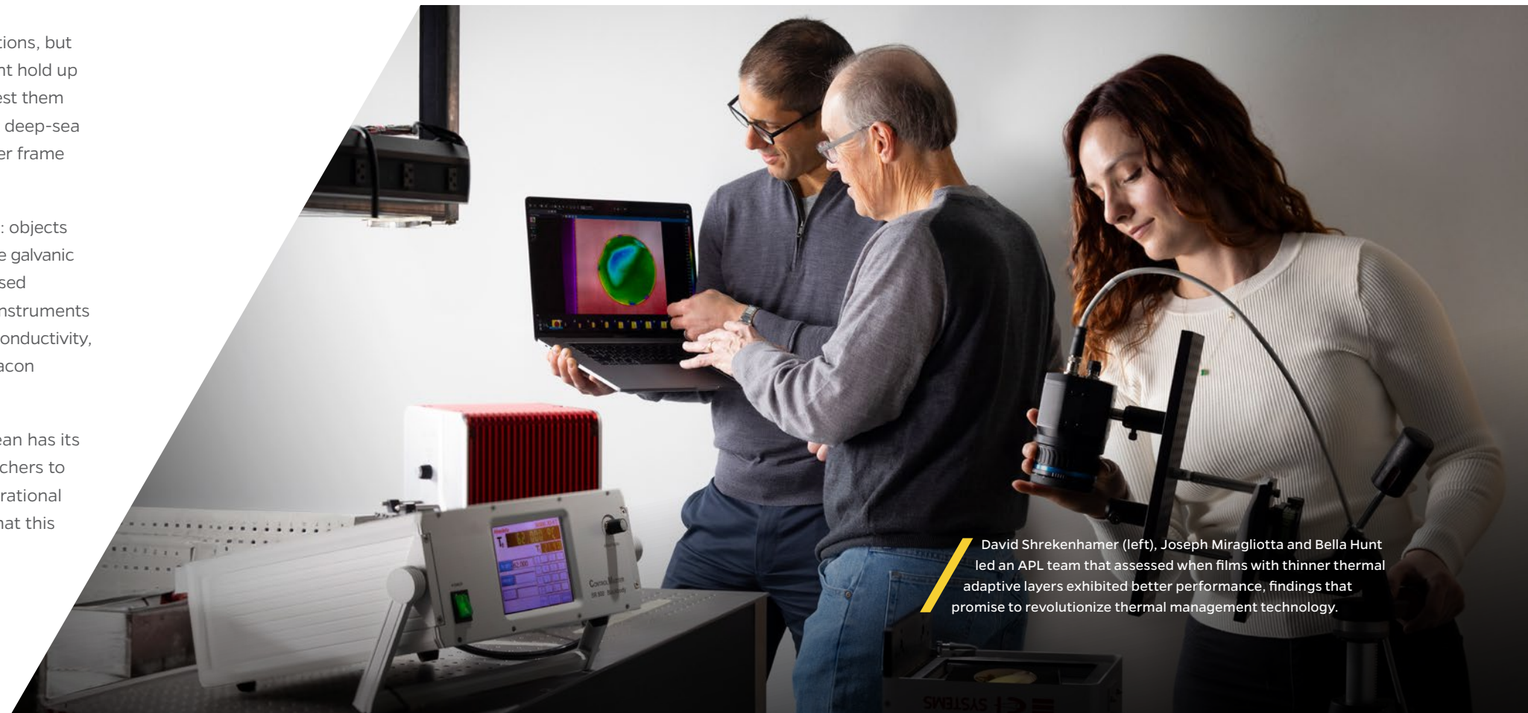
Some facilities on land can simulate these conditions, but the best way to see how materials and equipment hold up under operational circumstances is to actually test them at sea. And APL is making it happen through the deep-sea lander platform, a highly configurable underwater frame with a flotation section and weights.

Researcher Kate Chaffee explained how it works: objects under test are attached to the weights, which have galvanic releases that can be set to activate after an elapsed time — allowing the entire unit and its attached instruments to rise to the surface. The lander also features a conductivity, temperature and depth gauge and a satellite beacon for recovery.

Although testing at great depth in the open ocean has its risks, the lander allows APL and sponsor researchers to assess equipment and materials under real operational conditions. Project manager Clara Smart said that this is especially important for testing materials because sea temperature and extreme salinity cannot be easily reproduced on land.

"Work with this type of lander is relatively new for APL, but with the U.S. military's growing need for more undersea and seabed-based systems, there is a greater desire for more testing at depth," Smart said.

"Traditionally, deep ocean testing is outrageously expensive. That's one of the key elements of a modular platform like this — it requires relatively simple logistics, and it's relatively inexpensive."



David Shrekenhamer (left), Joseph Miragliotta and Bella Hunt led an APL team that assessed when films with thinner thermal adaptive layers exhibited better performance, findings that promise to revolutionize thermal management technology.

> “Sometimes, innovation comes from the simplest of places. In this case, the team achieved an integral power breakthrough by asking the question: ‘Will aluminum dipped in nickel work?’”
>
> — **Yo-Rhin Rhim,** Materials Scientist and Battery Project Principal Investigator

In APL’s thermal battery, an electric igniter activates nickel-aluminum heat pellets, setting off a chain reaction that melts the electrolytes, activates the rest of the battery and powers the system it is attached to.

## Building a Better Thermal Battery

APL researchers have developed materials that enable a new thermal battery for national security applications. The battery utilizes a nickel-aluminum heat source and offers several performance enhancements, including improved power density, increased operating times and decreased operating temperatures and size.

As missile systems became faster and more complex over the last several decades, the Navy’s Program Executive Office for Integrated Warfare Systems was interested in developing a battery to support them. As the technical direction agent for Standard Missile programs, responsible for performing critical experiments and developing prototypes that address missile limitations and advance capabilities of Navy systems, APL answered that call.

The team’s goal was clear: to build a thermal battery with a smaller footprint and higher power density. After promising early results, APL engineers expanded and fine-tuned their work with support from the Navy’s Surface Ship Weapons program and the Office of Naval Research.

To make a smaller but more powerful battery, the team had to change the electrolyte and cathode materials within it, but advancements in thermal battery component chemistries had not changed for several decades. To change those chemistries, the team had to take a step back and adjust the heat source.

Anodes, cathodes and electrolytes are the three basic building blocks for batteries. To use power from a battery in a phone or car, the electrolyte must shuttle ions from the negative side of the battery, called the anode, to the positive side, called the cathode. The electrolytes in those batteries are typically organic solvents. In thermal batteries, the electrolyte begins as a solid, allowing it to be stable and inactive for long-term storage. Once the heat source ignites to melt that salt, the battery suddenly becomes electrochemically active.

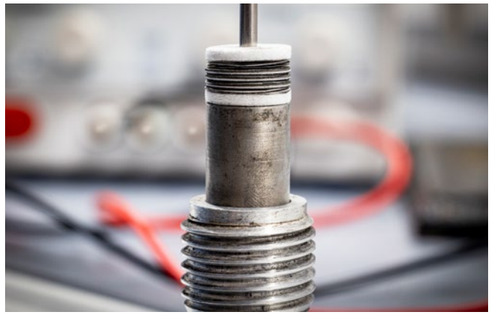
In thermal batteries, there’s a fourth component — a heat source, or heat pellets. Most heat pellets are a combination of iron metal powder and potassium perchlorate, and while extremely dependable, they don’t cooperate well with the varying chemistries the team was analyzing for new cathodes and electrolytes.

In APL’s thermal battery, an electric igniter activates nickel-aluminum heat pellets, setting off a chain reaction that melts the electrolytes, activates the rest of the battery and powers the system it is attached to. The team’s developments resulted in a battery that is roughly 60% smaller than most thermal batteries used today.

“When we were looking for cheaper heat source solutions, we were thinking, ‘I wish we could get aluminum foil, dip it in nickel and just see if it works,’” said Yo-Rhin Rhim, materials scientist and principal investigator on the battery project. “So we went to the store, got several types of aluminum foil and then electrolessly deposited nickel onto it and lit it with a match.”

The team began refining those parameters and perfecting the chemistries. One of the biggest challenges it faced was making sure that once the battery was ignited, it fired fully and the materials within became molten and were properly contained so they wouldn’t leak and short the unit. To overcome those challenges, the team developed an energetic mesh capable of both capturing the molten material and releasing additional heat, upon battery ignition, to enhance propagation of the heat pellet.

APL partnered with Sandia National Laboratories, a leading thermal battery manufacturer for Department of Defense applications, to build and test its prototype. In February 2023, the battery, comprising a suite of APL proprietary technologies, completed several successful rounds of testing.



A three-cell stack version of APL’s thermal battery ready for testing. The stacks contain a cathode, an electrolyte separator, an anode and a pyrotechnic thermal energy source — in this instance, nickel-aluminum.

To make a smaller but more powerful battery, APL energetic-materials chemist David Burns and colleagues had to change the electrolyte and cathode materials within it.

# Creating Food From Air

It sounds like something from science fiction, but the capability to create food from air shows real promise in addressing the challenge of feeding people during times of crisis or conflict.

APL chemical and biological engineer Collin Timm leads one of four teams selected for Cornucopia, a Defense Advanced Research Projects Agency (DARPA) program. In 2023, he led the APL team in its effort to produce nutritionally complete foods anywhere in the world. The team's idea was to use electricity to capture water, carbon dioxide, nitrogen and trace minerals from the air and then produce a rich, glucose-based material (called feedstock) on which to grow microbial food products.

The team, which dubbed its approach RePLICaTE — for Reducing Provisions and Logistics Inputs through Calorie Transformation from Electricity — is focused on delivering a working prototype that demonstrates a leap forward in food production on demand. Collaborators on the project include Johns Hopkins University, North Carolina State University and Meridian Biotech.

Feedstock is a raw material that is used as fuel or converted to another form of fuel or energy product — just as crude oil, for example, is the feedstock for gasoline. APL's process includes generating a central, rich feedstock from the components in air to support the growth of food microbes. The team captures carbon dioxide from the air and reduces it into simple organic molecules, such as formate and acetate, using sequential chemical reactions. Those products, in turn, are converted into sugars.

To develop these upstream complex processes, APL collaborated with experts at the Johns Hopkins Ralph O'Connor Sustainable Energy Institute who specialize in creating useful products from atmospheric carbon. The researchers extracted all of the key nutrients that microbes need to produce food from the air, even dust and particulate matter like iron and magnesium, which are needed for nutritionally complete foods.

So for all that effort, how does this engineered food taste?

"We are attempting to genetically engineer the production of vitamins and flavor components, like butter or vanilla, in organisms generally regarded as safe by the FDA for human consumption," said Julie Gleason, a molecular biologist at APL.

In addition to the flavor engineering work led by APL, Meridian Biotech is identifying nutritious microbes and processing them into food formats. Meridian's texturization process converts bacteria and fungi into ready-to-eat microbial shakes, bars and jerkies. North Carolina State University brings expertise in developing novel technologies for engineering diverse organisms.

The team is aiming to integrate these chemical and biological operations into a single process and eventually develop a manufacturing and housing system that could fit on the back of a truck, which deployed troops could use to make nourishing and appetizing food on demand in remote locations during field operations and disaster relief efforts.

Read more about how this technology came to be on page 86.


Responding to DARPA's Cornucopia challenge, an APL team created a concept for a food-creation system, called RePLICaTE, that fits in the payload capacity of a standard Humvee.

# Securing Communications in a Cyberattack

A novel APL-developed communications technology that provides secure access to networks facing outages or under cyberattack earned funding from the Department of Homeland Security's Commercialization Accelerator Program.

APL's Out-of-Band over Existing Communication (OBEC) technology allows a new, physically isolated out-of-band (OOB) network to be created on an existing Ethernet infrastructure, without additional networking equipment or wireless connections. An OOB network is a separate network used to manage and troubleshoot the primary, in-band network.

"Network connectivity is critical to the operation and management of industrial facilities and their processes," explained OBEC co-inventor Alexander Beall. "Cyberattacks against an industrial control network itself can have widespread and severe consequences, endangering the safety of operators, halting critical operations and resulting in costly downtime."

According to Beall and OBEC co-inventor Joseph Maurio, OOB communication allows for network resiliency, situational awareness and secure management of networked devices by creating alternate communication paths to manage network infrastructure devices. These alternate paths isolate nonessential traffic from operational traffic, preventing hackers from harming network operations or compromising network infrastructure.

However, traditional physically isolated OOB networking is expensive, requiring duplicative infrastructure or costly wireless devices — but not OBEC. Small, discrete modules can be installed at network endpoints and stacked at networking equipment. This technology can also be incorporated within the enclosures of new network equipment, further reducing the space and equipment needed to add OBEC to a network and ultimately enabling monitoring capabilities for a variety of needs across critical infrastructure sectors.

The Out-of-Band over Existing Communication (OBEC) device is a novel communications technology geared toward providing secure access to networks facing outages or under cyberattack.

**"Network connectivity is critical to the operation and management of industrial facilities and their processes."**

— **Alexander Beall,** Out-of-Band over Existing Communication Co-inventor

# DEFINING INNOVATIONS

Among APL's thousands of critical contributions to national security and space exploration are a number of Defining Innovations: game-changing breakthroughs in technology that have created inflection points in history. These revolutionary advances have ignited new engineering accomplishments globally, saved lives and secured the United States against threats at home and abroad. In 2023, the Laboratory closed its 80th anniversary celebration by unveiling two new Defining Innovations — Ballistic Missile Defense From the Sea and Planetary Defense — which join the nine Defining Innovations previously identified during APL's 75th anniversary.

## Ballistic Missile Defense From the Sea


APL responded to the critical challenge of proliferating ballistic missile threats, leading the development of the transformational system needed to demonstrate Ballistic Missile Defense (BMD) From the Sea. The resulting experiments proved that BMD technology could be integrated with a Navy weapon system to "hit a bullet with a bullet" in space from the sea. APL's critical contributions opened the door for the Navy's central role in BMD. The resulting impact is felt far beyond our nation's shores as BMD now provides enduring defense at sea and ashore across the globe.

# Planetary Defense


For more than a decade, APL engineers and scientists developed game-changing concepts and technologies to prove that it was possible to defend our planet from an asteroid on a potentially catastrophic Earth-impact trajectory. APL established the technological basis for planetary defense; solidified the domain as a research and development area at the federal level; played key roles in defining and exercising interagency and international coordination responsibilities; and captured worldwide attention by successfully completing the DART mission (depicted here), the first in-space demonstration of planetary defense technology.

Learn more about our first nine Defining Innovations and download a digital poster.









# EXPLORING THE EXTREMES

Whether they are robotically exploring the edge of the solar system, probing the frigid waters of Earth's poles or developing materials to protect technology from the blistering temperatures of hypersonic speed, APL scientists and engineers push the capabilities of technology to their limits. Leveraging decades of experience in space exploration, research and development, testing, prototyping and computational modeling, APL innovators are exploring the extremes to address the critical threats and challenges facing the nation and the world.

APL researchers are making novel measurements that will help validate computational models of materials in challenging hypersonic environments. Optical engineer Sara Margala is testing advanced materials in THE FORGE lab.

# Collaboratively Testing Materials at the Extreme

Hypersonic vehicles continue to present unprecedented challenges, particularly in the realm of materials. One pressing need is for materials that can serve as radomes and conformal windows — structures that can not only withstand speeds above Mach 5, temperatures well over 1,800 degrees Fahrenheit (1,000 degrees Celsius), atmospheric oxidation and tremendous aerodynamic shear loads, but are also transparent to electromagnetic signals.

For the past three years, APL materials scientists, thermal engineers and weapons systems specialists have been collaborating to understand operational needs and how they translate into unique requirements for advanced materials. Higher-survivability materials, for example, would enable forward-looking or downward-facing radome systems for targeting distributed adversary threats.

The APL team first conceptualized possible materials and conducted proof-of-principle demonstrations and then studied the electromagnetic properties of candidate materials in detail. The group has accomplished repeatable fabrication of window materials utilizing novel chemistries that provide significant advancement over current state-of-the-art materials in terms of thermal survivability, electromagnetic performance and manufacturability.

Extreme environment characterization and testing advancements were achieved in parallel with the materials work over the past three years, allowing material thermal survivability and electromagnetic performance to be tested under increasingly realistic hypersonic conditions. Looking forward to potential operationalization of the technologies, researchers are studying manufacturing approaches for large 3D structures, as well as strategies for integrating the windows into hypersonic vehicle structures.

Testing materials is integral to continuing to move this research forward. With that in mind, APL and the University of Colorado Boulder partnered first in 2023 to better understand and eventually predict the wear on and damage to thermal protection systems (TPSs) placed on hypersonic vehicles and spacecraft. That partnership was expanded later in 2023 with a master research agreement that opens new avenues for collaboration to address critical national security objectives and workforce needs. Both organizations are members of the University Consortium for Applied Hypersonics — a nationwide network seeking to deliver the innovation and workforce needed to advance hypersonic flight systems supporting national defense — and aim to provide results that engineers could leverage to inform testing and evaluation activities examining TPS resiliency.

"Forming strategic partnerships with universities gives APL another way to contribute to advancing science and technology, applying them to some of the questions we want to answer and accelerating technology transition to the warfighter," said Kerri Phillips, the chief scientist in APL's Air and Missile Defense Sector. "I hope this is the first of many successful ventures with our academic partners as we mature this partnership and conduct more critical experiments."

APL experts are collecting data that will ensure the robustness of defense systems today and provide data and experimental capabilities that can be leveraged to enhance the systems of tomorrow.

Back on APL's Laurel, Maryland, campus, the Laboratory is utilizing its Hypersonic Optical Test Facility (HOTF) to examine materials for a variety of high-speed aeronautical applications. HOTF is part of APL's Twin High-Energy Facilities for Optical Response Generation and Evaluation (THE FORGE), where researchers test materials using multikilowatt lasers.

Both labs carry out a range of experiments and tests on materials and structures. In the HOTF, researchers simulate the blistering temperatures materials endure during hypersonic flight and characterize physical and optical changes to materials exposed to high temperatures. In THE FORGE, researchers use high-powered lasers to test missile defense applications.

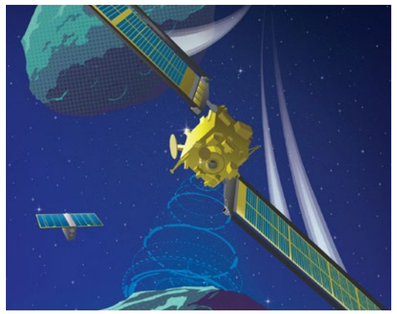
> **"Forming strategic partnerships with universities gives APL another way to contribute to advancing science and technology, applying them to some of the questions we want to answer and accelerating technology transition to the warfighter."**
>
> — **Kerri Phillips,** Air and Missile Defense Sector Chief Scientist

APL researchers hope to better understand and eventually predict the wear and damage affecting thermal protection systems (TPSs) on hypersonic vehicles, providing analyses and information engineers could leverage to inform testing and evaluation activities examining TPS resiliency.

## A Bullseye for Planetary Defense

Just five months after NASA's APL-led Double Asteroid Redirection Test (DART) mission struck its target asteroid on Sept. 26, 2022, team members published a series of four papers in the journal Nature that detailed the mission's results. They were nothing short of stunning. The history-making test run of a technique that could defend the planet from cataclysmic impact was highly successful at changing the path of the asteroid.

The mission's asteroid-deflection technique, known as "kinetic impact," was required to change the asteroid Dimorphos' orbit by at least 73 seconds to be considered a success. Instead, the impact decreased the time to complete an orbit by about a whopping 33 minutes. Debris ejected from the impact significantly contributed to that momentum change, the researchers found, amplifying the effect of the impact by a factor of 2.2 to 4.9. What's more, the fragments formed into a tail that trailed more than 40,000 miles (64,000 kilometers) behind the asteroid, making Dimorphos the first artificially formed "active asteroid"—an asteroid that looks a lot like a comet.



APL developed game-changing concepts and technologies to prove it is possible to defend Earth against a potentially catastrophic asteroid impact. See page 40 for more on APL's two newest Defining Innovations.

Overall, the mission clearly showed that kinetically impacting an asteroid can effectively change that asteroid's speed and future path—a conclusion that marks a huge step toward the goal of having the technology and knowledge to prevent an asteroid or comet from striking Earth.

"We are so proud of the DART team," said Jason Kalirai, APL's Space Formulation Mission Area executive. "The DART investigation's results demonstrate how successful the kinetic impactor technique can be and pave the way for a bright future for planetary defense.

> **"The DART investigation's results demonstrate how successful the kinetic impactor technique can be and pave the way for a bright future for planetary defense."**
>
> — **Jason Kalirai, Space Formulation** Mission Area Executive






NASA's DART spacecraft tested an asteroid-deflection technique known as "kinetic impact"—effectively slamming into the asteroid moonlet Dimorphos to change its orbit—and its success marked a huge step toward having the technology and knowledge to prevent an asteroid or comet from striking Earth.

APL scientists are focusing on the geology and other surface properties of the Moon, including large regions near the lunar South Pole where the crew members of NASA's Artemis 3 mission are expected to land. The permanently shadowed craters in these areas hold water ice that offers clues about the solar system's history and could be a source of drinking water and rocket fuel for astronauts. Credit: NASA/Goddard Space Flight Center/University of Arizona

# Unveiling the Secrets of the Moon and Sun

APL researchers have increasingly set their sights on the two largest objects in our sky: the Sun and the Moon. As space becomes easier to access through the proliferation of commercial launch vehicles, cislunar space—the space between the lunar surface and the large swath of space between Earth and the Moon—is poised to become the world's next great frontier.

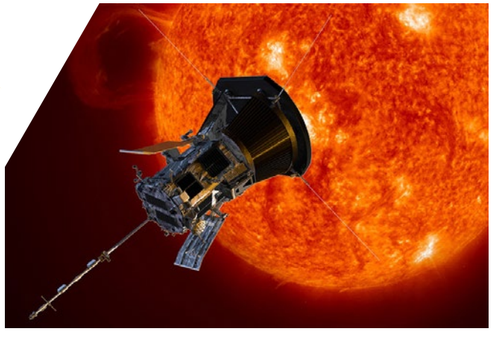
NASA selected a team led by APL planetary scientist and Space Science and Instrumentation Branch Supervisor Dana Hurley to collaborate on lunar science and lunar sample analysis research under the agency's Solar System Exploration Research Virtual Institute (SSERVI), a virtual collective charged in part with answering questions about the Moon.

Called RASSLE (short for the Research Activities Supporting Science and Lunar Exploration), the new team of researchers from 15 institutions around the world will investigate fundamental processes on the lunar surface. Particular attention will be given to the cooling and crystallization of the Moon's upper mantle, the source and redistribution of volatiles like water across the Moon, and methods for handling and analyzing samples that contain volatiles. The team will study the Moon's South Pole–Aitken Basin, where there may be exposed material from the Moon's mantle, and permanently shadowed craters, which hold water ice that has both scientific value as a time capsule of the solar system's history and resource value for astronauts, to generate drinking water or rocket fuel.

"RASSLE is a great opportunity to lay a scientific foundation for the future of lunar exploration," Hurley said. "Our research will address three of the highest-priority areas in lunar science, guided by the questions NASA needs to consider to plan for the robotic and human missions that will establish a permanent presence on the Moon."

Within the extreme conditions around Earth's star, NASA's Parker Solar Probe, which APL built, operates and manages, has racked up an impressive list of superlatives in its first five years of operations: It is the closest spacecraft to the Sun, the fastest human-made object and the first mission to ever "touch the Sun." In 2023, Parker added one more feather to its Sun-kissed cap by becoming the first spacecraft ever to fly through a coronal mass ejection (CME) early in the CME's evolution so close to the Sun.

These fierce eruptions can expel magnetic fields and billions of tons of coronal material (plasma or ionized gas) at speeds ranging from 60 to 1,900 miles (100 to 3,000 kilometers) per second. When directed toward Earth, these ejections can bend and mold our planet's magnetic field, generating spectacular auroral shows and, if strong enough, potentially devastating satellite electronics and electrical grids on the ground.



Artist's impression of Parker Solar Probe; the spacecraft's record-setting flights into the Sun's upper atmosphere are allowing it to gather unprecedented data on solar activity.

Cruising on the far side of the Sun just 5.7 million miles (9.2 million kilometers) from the solar surface—22.9 million miles (36.8 million kilometers) closer than Mercury ever gets to the Sun—Parker Solar Probe first detected the CME remotely before skirting along its flank. The spacecraft later passed into the structure, crossing the wake of its leading edge (or shock wave), and then finally exited through the other side.

In all, the Sun-grazing spacecraft spent nearly two days observing the CME, providing physicists with an unparalleled view into these stellar events and the first-ever opportunity to study them early in their evolution.

"This is the closest to the Sun we've ever observed a coronal mass ejection," said Nour Raouafi, the Parker Solar Probe project scientist at APL. "We've never seen an event of this magnitude at this distance."

Despite the eruption's power, the spacecraft seemed unfazed, experiencing nothing more than a slight torque—a tiny turn for which it autonomously compensated.

Beyond its close encounter with a CME, Parker made observations that offered scientists new insights that inch them closer to reaching the mission's primary science goal: uncovering the process that gives birth to the Sun's solar wind—the torrent of electrons, protons and heavy ions that constantly stream from the star's upper atmosphere, called the corona, and are accelerated to speeds up to nearly 2 million miles per hour (3.2 million kilometers per hour).

The team found that ubiquitous small jets, or "jetlets," in the corona are likely responsible for heating and accelerating solar wind plasma. Analysis of the rate, mass and energy fluxes of this small-scale jetting can account for essentially all the mass and energy lost by the Sun to the solar wind.

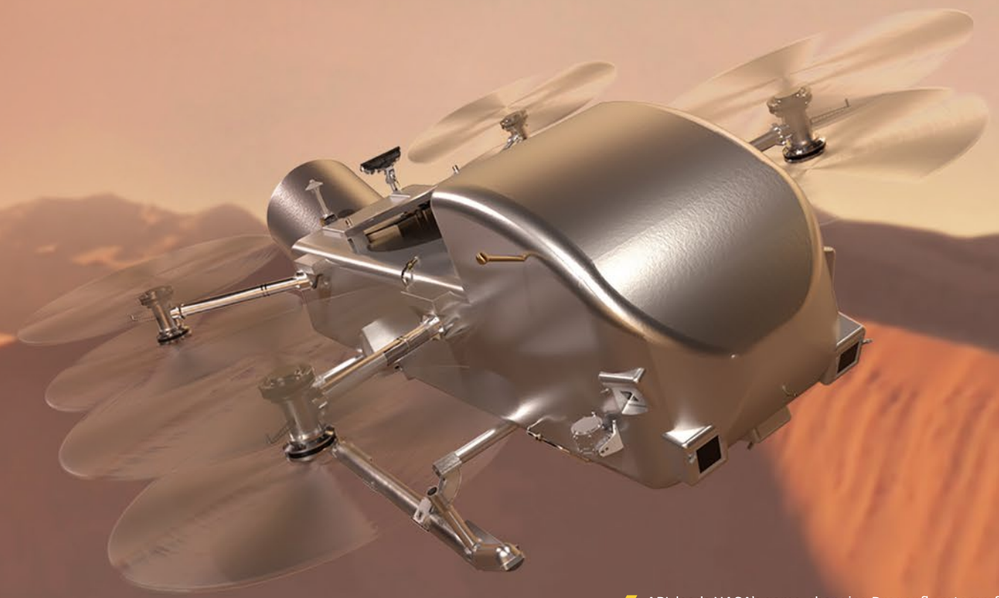
"You can see the flow of the solar wind rising from tiny jets of million-degree plasma all over the base of the corona," Raouafi said. "Our findings will have a huge impact on humankind's understanding of two major processes on the Sun: the heating and acceleration of the coronal and solar wind plasma."

In 2024, Parker Solar Probe will come within 3.8 million miles (6.1 million kilometers) of the solar surface.

**"Our research will address three of the highest-priority areas in lunar science, guided by the questions NASA needs to consider to plan for the robotic and human missions that will establish a permanent presence on the Moon."**

— **Dana Hurley,** Planetary Scientist and Space Science and Instrumentation Branch Supervisor

> **We are ready to continue our work on the next phase of Dragonfly development, including testing in the large Titan-environment chamber here at APL."**
>
> — **Elizabeth "Zibi" Turtle**, Dragonfly Principal Investigator



APL leads NASA's game-changing Dragonfly rotorcraft mission, which centers on characterizing the habitability of Titan's mysterious environment and investigating the progression of prebiotic chemistry.

# Marking Major Milestones for Missions Exploring the Outer Solar System

Saturn's largest moon Titan touts being not only the solar system's sole moon with a thick atmosphere but also the only world known to have an active hydrologic cycle that produces rain, rivers, lakes and seas of liquid methane. The abundant, complex, carbon-rich material on Titan's frigid surface and the past presence of liquid water make the moon ideal for studying how far organic synthesis can progress in an environment that has provided the ingredients necessary for life as we know it.

NASA's pioneering rotorcraft mission Dragonfly, which APL leads, centers on characterizing the habitability of Titan's mysterious environment and investigating the progression of prebiotic chemistry there, where carbon-rich material and liquid water may have mixed.

With the mission scheduled to launch in 2028, the Dragonfly team passed a preliminary design review in March 2023, crossing a major milestone required of all NASA missions. The weeklong review included 60 presentations to an expert panel and covered topics such as spacecraft design, mission requirements, science plans, schedule, cost and risk.

"The team did a fantastic job," said Dragonfly Principal Investigator Elizabeth "Zibi" Turtle from APL. "We're incredibly excited to have completed this step and are ready to continue our work on the next phase of Dragonfly development, including testing in the large Titan-environment chamber here at APL."

The team behind NASA's Interstellar Mapping and Acceleration Probe (IMAP) mission similarly crossed a critical design review milestone in 2023, reviewing the designs of the spacecraft's subsystems and 10 instruments before development begins.

IMAP, which APL is building in partnership with Princeton University, will explore the edge of the solar system and map and characterize particles streaming from both the Sun and the galaxy beyond.

Looking far out into the solar system and into the past, APL researchers dove back into the nearly 40-year-old energetic particle data from the APL-built Low Energy Charged Particle instrument aboard NASA's Voyager 2 spacecraft and uncovered surprising evidence that could add Uranus to the list of planets with at least one active ocean moon.

Dragonfly team members gather in front of the Titan Chamber — with the Dragonfly thermal development test module (DTM) still inside — after successful completion of the chamber's first tests. Credit: NASA/Johns Hopkins APL

Spurred by growing momentum in the planetary science community to revisit Uranus, one of the solar system's ice giants, the analysis found that a peculiar population of trapped energetic particles around the equator of Uranus' magnetic field likely arises from the moons Ariel and/or Miranda. The team suspects the particles arise either from sputtering — the process of high-energy particles ejecting surface particles into space — or (more tantalizingly) from vapor plumes similar to those seen on Saturn's icy ocean moon Enceladus.

"We've been making the case for a few years now that energetic particle and electromagnetic field measurements are important not just for understanding the space environment but also for contributing to the grander planetary science investigation," said APL scientist Ian Cohen, who led the study. "Turns out that can even be the case for data that are older than I am. It just goes to show how valuable it can be to go to a system and explore it firsthand."

Given that Voyager 2 is the only spacecraft to have ever gone to Uranus — passing in a single flyby — the team noted there is no way to definitively determine the particles' source without a return mission to collect new data at the planet. "We can always do more comprehensive modeling," Cohen said, "but until we have new data, the conclusion will always be limited."

# Probing New Frontiers at Earth's Poles

In February 2023, APL researchers rode aboard Lindblad Expeditions' National Geographic Resolution cruise ship to the frigid seas of Antarctica, where they coupled their biology and oceanography expertise to demonstrate a whole new analytical capability for monitoring global biodiversity and the changing climate.

Building on previous work done in the Arctic to set up and test a rapid genetic analysis platform for environmental DNA (eDNA), APL molecular biologist Peter Thielen installed a similar platform for long-term research capabilities in the Southern Ocean.

Like other types of environmental forensic data, eDNA — the genetic material that animals slough off into the environment through hair, skin, blood and other cellular sources — provides a snapshot of the organisms that either were or still are in an area. That makes it valuable for monitoring biodiversity, detecting invasive species, tracking endangered species, checking water quality and assessing the density of harmful bacteria. And with the platform fitted to have repeated access to the same regions at the same time each year, it will also collect important data for understanding the climate and how it is changing.

"The ability to use a water sample as a forensic identification tool is a transformational change in the way we observe biological activity in the ocean," Thielen said. "APL research and engineering projects are pushing the boundaries of what can be done with eDNA technology, and we're now beginning to realize the full potential of these capabilities."

Scientist David Porter also ventured to the Antarctic to apply his expertise in physical oceanography, aiding researchers' efforts to better link biological phenomena, such as massive accumulations of krill — the tiny crustaceans that form the foundation of Southern Ocean's food chain — with oceanographic dynamics.

"We're merging a new technology base with a well-established discipline and trying to get the right people in the right places at the right times to accelerate both fields of study," Thielen said.

eDNA analysis is a relatively new field of research that has emerged as an exciting way to study ocean biodiversity — and has the potential to serve as a global biological monitoring capability.

Another team of APL researchers investigated the potential impact of climate change on communications and remote sensing systems like radar and infrared cameras. The team's investigation determined that dramatic changes to Earth's climate would have effects split both ways — some for better, some for worse.

"We wanted to ask whether climate change will alter the environment enough to impact sensor system designs, because if it does — even a little bit — that would be a surprise for designers and engineers who aren't used to thinking about the environment as an evolving design factor," said Jonathan Gehman, an applied physicist at APL.

The team examined environmental data important to the effectiveness of sensors, such as moisture and sea surface temperatures, from seven locations around the world, investigating them under various emissions scenarios. In nearly all seven locations, high-emission scenarios led to changes that would have some impact on future sensor designs. The two Arctic locations analyzed showed the most dramatic change, which is consistent with expectations that the Arctic is disproportionally impacted by climate change.

Other environmental changes, such as rainfall, cloud cover and aerosol density, may have similar contributions but have yet to be examined. "We've looked at a very narrow slice of effects on technology in this initial study, but it's clear that the effects of climate change should be on everyone's radar screens," Gehman said.

Molecular biologist Peter Thielen touches a floating piece of ice while venturing out into open Arctic waters. The ability to take a water sample and use it as a forensic identification tool is a transformational change in the way researchers observe biological activity in the ocean.

# COUNTERING EVOLVING THREATS

Disruptive technological advances, a rapidly changing climate, emerging infectious diseases and other developing threats challenge our nation like never before. Drawing on decades of experience in systems engineering, research and development, and analytics, APL anticipates and responds to these and various other threats to support national security priorities. By combining creativity and technical expertise within a culture of innovation, APL is tackling increasingly difficult challenges with impacts across multiple domains.

APL's application of AI to predict climate tipping points uses adversarial-based deep learning networks. Jennifer Sleeman (right), Jay Brett and their team conduct their research in APL's Intelligent Systems Center.

> **"A more accurate, higher-resolution model can help protect populations by providing them with information about air quality further ahead of time so that they can better plan ahead."**
>
> — **Marisa Hughes,** APL Climate Intelligence Lead

## Addressing Capability Gaps in a Changing Climate

The Earth's changing climate presents new challenges to communities, militaries, equipment and infrastructure around the world.

In response, APL researchers are applying expertise in artificial intelligence (AI), data science, modeling, advanced prototypes and materials development to create tools and technologies that can help the world adapt and mitigate these changes.

Scientists and policymakers alike have their eyes on climate tipping points, the critical thresholds that, once crossed, could tip a natural climate system into an entirely different state. The impacts are difficult to capture with accuracy or confidence because of the complexity and dynamics of the interconnected Earth systems involved.

To overcome these challenges, APL teamed up with oceanographers from the Johns Hopkins University Department of Earth and Planetary Sciences to blend AI with traditional modeling methods to predict climate tipping points and, perhaps, avoid crossing them in the first place. The project — the Physics-informed AI Climate Model Agent Neuro-symbolic Simulator (PACMANS) for Tipping Point Discovery — was supported by the Defense Advanced Research Projects Agency (DARPA) as part of its AI-assisted Climate Tipping-point Modeling (ACTM) program.

"We created a simulated AI environment using adversarial-based deep learning networks," said Jennifer Sleeman, a senior AI researcher and PACMANS principal investigator. "One is perturbing and generating tipping points, and the other is learning to recognize a tipping point and how to modify conditions to move away from a tipping point."

The team also wanted to develop a new language that will enable translation between "what-if" questions and the simulated AI environment. It took on one of the dozen natural systems at risk of tipping — the Atlantic Meridional Overturning Circulation (AMOC), which serves as a global conveyor belt of ocean water from the warm South Atlantic to the colder North Atlantic — as a use case. The team leveraged deep learning methods, neuro-symbolic representations and Johns Hopkins-developed surrogate ocean models to build a tool that can predict conditions that may lead to a collapse of the AMOC — a scenario that could have long-term negative effects on food security, sea levels, delicate ecosystems and the Arctic.

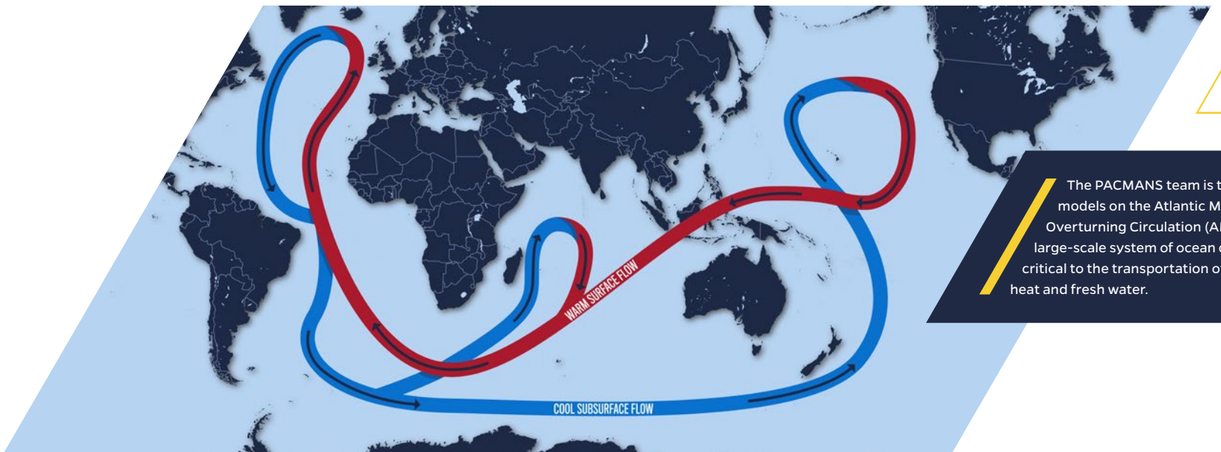
Forecasting atmospheric composition is another critical aspect of environmental and climate monitoring, especially when it comes to tracking the effects of extreme air quality events — like the 2023 Canadian wildfires — on human health and safety. While forecasting models exist, their need for information on hundreds of chemical species and the physical atmosphere makes them computationally expensive — and that makes them difficult to run in near real time and leaves a lot of uncertainty in the estimates.

APL set out to address the problem by building deep learning models that could emulate the slower models and forecast further into the future. Along with the National Oceanic and Atmospheric Administration, NASA Goddard Space Flight Center and Morgan State University, an APL team examined whether deep learning methods could realistically estimate air quality models in place of running costly simulations.

"We know that dangerous air quality levels are a significant threat, but because exposure happens slowly, over time it is more difficult to quantify," said Marisa Hughes, the climate intelligence lead at APL. "A more accurate, higher-resolution model can help protect populations by providing them with information about air quality further ahead of time so that they can better plan ahead."

Hughes is also leading the APL team that supports Climate TRACE, a coalition that is monitoring greenhouse gas emissions on a global scale. APL developed a hybrid approach to accurately estimate road transportation emissions by combining machine learning, road network data and satellite imagery with localized emissions factor data such as information about vehicle types. In 2023, the team's methodology was peer reviewed and published by Cambridge University Press, establishing an accurate, globally scalable and easily configurable greenhouse gas monitoring framework. Their efforts also helped Climate TRACE expand their database, which now tracks greenhouse gas emissions from more than 352 million assets globally, up from 80,000 in 2022.

And while several Laboratory teams are using AI to identify and characterize critical climate challenges, others are focused on reducing emissions directly by making buildings more efficient. One Laboratory team infused methods to reflect light into a coating to reduce building temperatures, while another used deep reinforcement learning (DRL) methods to improve control of heating, ventilation and air conditioning systems that account for a significant portion of global energy consumption. This added level of control could help lower carbon emissions, with some DRL-based controllers showing the potential to reduce a building's energy consumption by 10% or more.




The PACMANS team is testing its models on the Atlantic Meridional Overturning Circulation (AMOC), a large-scale system of ocean currents critical to the transportation of heat and fresh water.

# Assuring Autonomous Operations

While advances in AI and autonomy are accelerating the pace of research, they also raise issues of trust and safety. The successful implementation of AI-enabled advances will depend on public confidence — and APL is integral in verifying that the nation can trust in the AI systems it employs to perform a wide range of tasks.

As more and more uncrewed aerial systems (UASs) enter the airspace, concerns over air traffic management and safety increase as well. Building on a strong foundation of work in applying AI and machine learning to ensure the safety of the next generation of passenger aircraft, APL is laying the groundwork for the incorporation of these uncrewed systems in the years ahead.

Focused on safety, APL partnered with the Federal Aviation Administration, the Massachusetts Institute of Technology Lincoln Laboratory, the MITRE Corporation and several other leading organizations to develop a new Airborne Collision Avoidance System (ACAS) that will gradually replace the current system now aboard large passenger aircraft worldwide.

The new system, known as ACAS Xa, modernizes and improves the already successful ACAS platform. ACAS Xa detects nearby aircraft by receiving sensor measurements from onboard surveillance systems and estimates the relative position and speed of these aircraft by using tracking algorithms. The system then evaluates potential pilot actions and decides on the best option. If necessary, ACAS Xa sends a collision-avoidance alert directly to the pilot's flight deck display.

ACAS Xa introduces additional surveillance data and optimized resolution advisories without changing the cockpit interface, alerts or presentation. This system was officially published as a new international standard in 2018, after successfully logging hundreds of millions of simulated encounters and passing rigorous evaluations by professional pilots.

With ACAS Xa as the foundation, APL is building a family of ACAS X standards that will accelerate the entry of UASs — including large UASs (ACAS Xu), small UASs (ACAS sXu) and rotorcraft (ACAS Xr) — into the airspace. The interoperable family of ACAS X standards for UASs will all be published by 2026, ensuring that these innovative systems will be able to safely share the skies with passenger aircraft.

Josh Silbermann, ACAS X project manager, said the expected infusion of millions of commercial and recreational drones into the nation's airspace represents a huge opportunity to enable routine autonomous operations such as search and rescue, precision agriculture and medical delivery — but it also presents challenges.

Software engineer Kaun Yim led the development of a graphical interface that simplifies the user experience for the Strategically Tasked Organic Radio frequency Machines (STORM), a capability that helps warfighters to maintain spectrum awareness, select targets on the battlefield and — importantly — keep out of harm's way.

> "We're one step closer to ensuring the safe integration of uncrewed platforms into an airspace traditionally used by piloted aircraft."

— **Josh Silbermann,** ACAS X Project Manager

> "It's satisfying to know that our work will enable our warfighters to monitor remote sensors without putting their lives at risk."

— **John Renda,** STORM Program Manager

"Thanks to the incredible work from our teams," he said, "we're one step closer to ensuring the safe integration of uncrewed platforms into an airspace traditionally used by piloted aircraft."

APL researchers are also enlisting AI to help warfighters maintain spectrum awareness and — most importantly — keep out of harm's way.

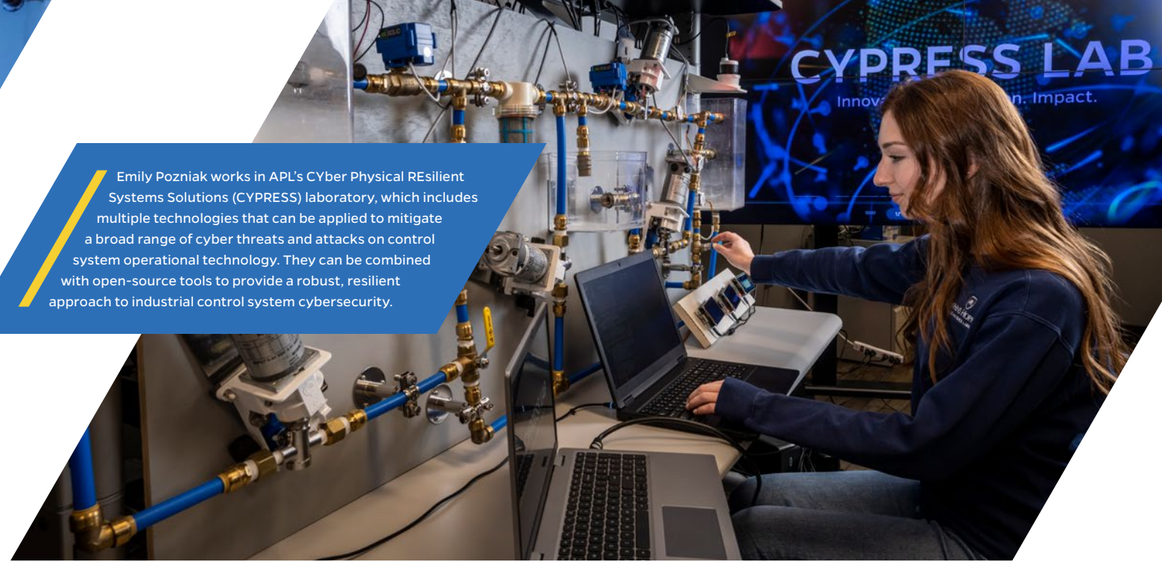
Known as Strategically Tasked Organic Radio frequency Machines (STORM), the capability has helped warfighters make sense of the electromagnetic chaos of war for the better part of a decade. In 2023, APL added a level of ease and functionality to STORM: a graphical interface that unifies and simplifies the user experience.

Tasked by the U.S. Army Combat Capabilities Development Command, also known as DEVCOM, Army Research Laboratory, a team of APL engineers delivered a STORM update that features a new "single pane of glass" interface to the 2nd Brigade Combat Team, 10th Mountain Division, at Fort Drum, New York. In an unexpected turn of events, John Renda, the STORM program manager at APL, found himself delivering the capability to his son, a heavy weapons company executive officer in the brigade.

"This is cutting-edge technology handed off directly to soldiers to enhance their operations," said Renda. "It's satisfying to know that our work will enable our warfighters to monitor remote sensors without putting their lives at risk."

Electrical engineer Kevin Phillips demonstrates a capability that helps warfighters make sense of the electromagnetic chaos of war.

APL worked with Cranberry Water Treatment Plant Superintendent Bret Grossnickle to implement a cost-effective, cyber-physical situational awareness capability at the facility.




Emily Pozniak works in APL's CYber Physical REsilient Systems Solutions (CYPRESS) laboratory, which includes multiple technologies that can be applied to mitigate a broad range of cyber threats and attacks on control system operational technology. They can be combined with open-source tools to provide a robust, resilient approach to industrial control system cybersecurity.

# Protecting People and Infrastructure Against Cyber Threats

New technologies, AI and deepfakes have made cyberattacks more elusive and damaging than ever. Cyberattacks on the nation's most critical systems could lead to service outages, damage to critical infrastructure and, potentially, illness and loss of life.

To address potential attacks, APL developed a cost-effective cyber-physical situational awareness capability for industrial control systems. The technology is designed to detect and alert operators to suspicious activity, such as unauthorized access, malicious code and data exfiltration. It also provides a comprehensive view of the system's health and performance, allowing operators to quickly identify and address any issues.

This solution combines network fingerprinting, host-based monitoring, digital twin technology and advanced event correlation and alerts to provide an operator with a detailed understanding of their systems. The suite of relatively inexpensive tools can be easily adapted to a facility's infrastructure.

The tools build on previous Laboratory work on a capability called MOSAICS (More Situational Awareness for Industrial Control Systems), which is aimed at integrating various technologies to provide comprehensive situational awareness and response capability for industrial control systems.

In 2023, APL applied its technology to the Cranberry Water Treatment Plant in Westminster, Maryland. The APL team tested the system by mimicking events, such as an unauthorized USB drive being left in a local workstation, an attempt to modify the speed of a chlorine pump above the normal operating range, and the creation of an abnormal network connection to the control network. The APL system successfully detected the unexpected behavior in all these scenarios.

> **"This work shows how APL can apply our technical expertise to big challenges in society at the nexus of technology, policy and norms."**

— **Antonio DeSimone,** Principal Technical Leader for National Security Communications

APL's solution — which is easy to deploy and maintain, cost-effective, scalable and usable in a variety of different environments — is one example of how the MOSAICS reference architecture can be adapted for a control system of any size.

In the physical world, the Red Cross, Red Crescent and Red Crystal are internationally recognized emblems of legal protection for the wounded, sick and those who care for them in armed conflict. As humanitarian relief and health care organizations increasingly rely on computer networks to help provide care, it is critical that there is a way to signal legal protection of the digital assets, services and data of these entities.

In the cyber world, APL is working in collaboration with the International Committee of the Red Cross (ICRC) to develop a technical framework to replicate the physical emblems — and the protection they signal — with the creation of a digital emblem. The emblem would signal the protected status of digital assets and thus indicate that they should not be targeted.

"While the physical emblem is already recognized under international law, it will take some time for governments to agree to the recognition of its digital equivalent," said Kerstin Vignard, a senior analyst at APL. "In the meantime, proving the technical feasibility of such an emblem is essential to building a norm which recognizes that the digital assets, services and data of medical and humanitarian entities should have the same legal protection in the digital world as they have in the physical one."

"It's hard to articulate a norm when there is not already behavior behind it," said Erin Hahn, managing executive in APL's National Security Analysis Department. "We know it helps to have a galvanizing principle that people can get behind. People can grasp the idea of a digital emblem. The emblem offers a small, concrete step to establish more common norms for cyber operations."

Principal technical leader Antonio DeSimone and scientist Brian Haberman led APL's research into the technical development of a digital emblem. The team looked at capabilities that could be added to existing infrastructure so that network service providers could leverage known technologies rather than deploying and learning how to use brand-new services.

This led APL to explore two primary mechanisms for a digital emblem: one domain name system (DNS) based and one Internet Protocol (IP) address based. A DNS-based emblem would add a visible label to the domain name or associate an attribute through a special record in the DNS to signify its status in an easily accessible way. An IP address-based emblem would apply semantics to a site's address to designate its protected status. This would build on an existing system that assigns IP addresses and allow systems anywhere on the internet to see whether systems or communications are associated with a protected entity.

The APL team is now creating prototypes for the two mechanisms and is working with the ICRC to test them alongside a third technical approach developed by ETH Zurich and the University of Bonn.


Emma Holmes is part of an APL team that is exploring and demonstrating how virtual and robotic assistants can support combat medics to improve care for injured warfighters.

## Rapidly Responding to Injury and Illness

The changing nature of warfare requires combat and civilian medics to treat casualties in new ways, such as by relying more on robotic assistants. APL researchers are harnessing the power of AI to support these next-generation medical collaborations.

APL has been working with the Army's Telemedicine and Advanced Technology Research Center (TATRC) to combine technologies that enable teamwork between medics, AI-based virtual assistants and autonomous robots.

Leveraging ongoing research on adaptive human–robot teaming — sponsored by the DEVCOM Army Research Laboratory and the Army Artificial Intelligence Innovation Institute and using APL internal grants — the Laboratory is developing a cognitive architecture for robotic skill acquisition. The successful test case involves humans wearing augmented reality headsets and collaborating with four-legged robots to perform reconnaissance and field care tasks, such as moving safely through an environment, searching for casualties and providing lifesaving care.

> **"What if we could teach robots the way we teach people — through written instructions, verbal instructions and gestures, and by example?"**
>
> **— David Handelman,** Senior Roboticist

"What if we could teach robots the way we teach people — through written instructions, verbal instructions and gestures, and by example?" asked David Handelman, a senior roboticist at APL. "We believe that new capabilities could be enabled by a wide group of instructors and subject-matter experts, thereby democratizing the process of robot training."

Teams from around APL are also working on tools to support the growing numbers of first responders who find themselves preparing for and responding to mass casualty events.

The Laboratory is working with the federal Biomedical Advanced Research and Development Authority (BARDA) to create the Resource-related Information and Tracking Medical Communications Application (RITCA). The prototype capability will provide real-time access to information about available medical resources during mass casualty incidents — whether natural disasters, accidents or planned attacks — and enable effective communications among emergency responders. It may also provide situational awareness to leaders of the U.S. Department of Health and Human Services' Administration for Strategic Preparedness and Response, under which BARDA falls.

APL teams are tapping the power of augmented reality and other innovative tools and techniques to develop technology that could help first responders provide emergency care in mass casualty or other catastrophic events.

The RITCA concept is being developed for trauma and burn care but has the ingredients to become an all-hazard response system. The system will empower timely peer-to-peer communications within trauma and burn care communities for emergency care and could eventually incorporate telemedicine capabilities for remote guidance and just-in-time training, delivering guidance precisely when and where a user needs it.

# Detecting Diverse Threats

Illicit substances and infectious diseases that cross our borders are a threat to national security and stability. Teams across the Laboratory are focusing on various methods to detect and fend off synthetic and biological threats.

In 2022, more than 70,000 Americans died from overdosing on synthetic opioids such as fentanyl. Stemming the tide of this tragedy requires a reliable means of detecting the drug, a task complicated by the creation of fentanyl analogs — synthetic molecules designed to mimic fentanyl's effects while evading traditional detection methods.

In response, a team of scientists at APL has developed machine learning algorithms that can find common patterns within fentanyl analogs based on data from physical detection methods and can detect new analogs based on existing ones. These algorithms are helping the government keep up with the never-ending chemical arms race that characterizes the drug war.

By training algorithms on data about known fentanyl analogs and their chemical structures, APL machine learning experts are able to play the same game as the criminals — but in reverse. The trained algorithms have been able to identify novel fentanyl analogs with an encouraging degree of accuracy.

This effort is part of a larger portfolio of APL machine learning work to identify dangerous unknown substances. The approach underlying these projects — training algorithms in pattern recognition so that they can determine whether an unknown substance is a threat — will be useful against all manner of emerging threats.

"To a soldier in the field, it most likely doesn't matter whether a chemical is a specific nerve agent — what matters is whether or not it's a nerve agent, and the forensics people can work out what exactly it is later," said Dave Lawrence, an organic chemist at APL. "This kind of generalized approach to the problem is only going to become more useful and relevant in the future."

Biothreat detection and characterization continues to be of the utmost importance globally as well as locally. Collaborating with colleagues from around the world, APL biologists are enabling time-critical responses to keep humans ahead of the next pandemic.

In 2023, bird flu infected scores of wild and domestic birds, sea lions, mink and bears, raising concerns about the virus's ability to mutate and spread into new populations. In one particular case, a young Cambodian girl and her father were infected with a highly pathogenic H5N1 avian influenza virus — the first time the virus had infected humans in Cambodia since 2014.

Using molecular biology protocols developed and optimized by APL researchers, the Virology Unit at the Institut Pasteur du Cambodge swiftly characterized the genome of the virus. Genome sequencing revealed that the virus belonged to a genetic subgroup of highly pathogenic H5N1 avian influenza circulating in poultry in Cambodia for over 10 years. This virus group is genetically distinct from highly pathogenic H5N1 avian influenza viruses responsible for animal outbreaks and sporadic human infections circulating in much of the world. This information was critical to assisting the local response and understanding the risk of further cases.


Chemist Dave Lawrence and colleagues are tapping the power of machine learning to identify dangerous substances — training algorithms in pattern recognition to quickly recognize whether an unknown substance is a threat.

The Laboratory has developed an impactful program to connect a breeding consortium with the tools, techniques and knowledge they need to better evaluate, train and employ explosive detection canines. Pictured (from left) are Kari Meidenbauer, David Deglau and officers from the University of Maryland Police Department, a closely partnered agency that offers key support to the Domestic Breeding Consortium. The canine friends — Hera and Hercules — were bred and developed within the consortium.

Using customized sequencing protocols and the Laboratory's own Basestack bioinformatics platform, APL researchers partnered with international colleagues to employ handheld sequencers and custom analysis software — enabling animal and public health groups to efficiently augment their traditional diagnostic methods with genetic characterization and helping researchers and health workers quickly make the data they gather available to the infectious disease surveillance community to guide international responses.

"There is an unmet need to assess new viruses as they emerge from nature," said APL virologist Claire Marie Filone. "Our goal is to identify if previously uncharacterized viruses are a cause for concern. Those are the viruses we need to consider for greater intervention or rapid detection tests."

APL-developed capabilities are making it easier to gather detailed genetic information, down to the viruses' common building blocks. The ability for individuals around the world to perform these detailed analyses enables faster responses as pathogens emerge within animal species.

With eyes on the future, APL is using next-generation analytical tools and computational models to understand potential evolutionary trajectories of viruses, adding to a toolkit of approaches that can be used to safely characterize pathogen genetic changes and their potential impact on humans and animals.

In the realm of animals enabling threat detection by humans, APL is working with academic and private-sector partners to shape innovative ways to breed, train and deploy canines to detect chemical and explosive and narcotic threats — addressing a shortage of domestically sourced and trained canines to fulfill a duty critical to national and local security.

One aspect of this multifaceted program incorporated genetic testing to determine the most desirable characteristics for canine health, cognition and temperament. This is done through high-fidelity genetic mapping with the goal of creating predictability for breeders.

In addition, the team developed technology and materials to support training needs and operational requirements, such as methods to keep the canines engaged in the training and deployment.

APL also leads the national Domestic Breeding Consortium on behalf of the Department of Homeland Security Science and Technology Directorate, focusing especially on the growing need for quality domestically bred canines.

*The research in this document on animals enabling threat detection by humans was conducted with the U.S. Department of Homeland Security (DHS) Science and Technology Directorate (S&T) under contract 70RSAT19CB0000002.*

**"Our goal is to identify if previously uncharacterized viruses are a cause for concern. Those are the viruses we need to consider for greater intervention or rapid detection tests."**

— **Claire Marie Filone,** Chief Scientist in APL's Biological Sciences Group

# LABS OF THE LAB

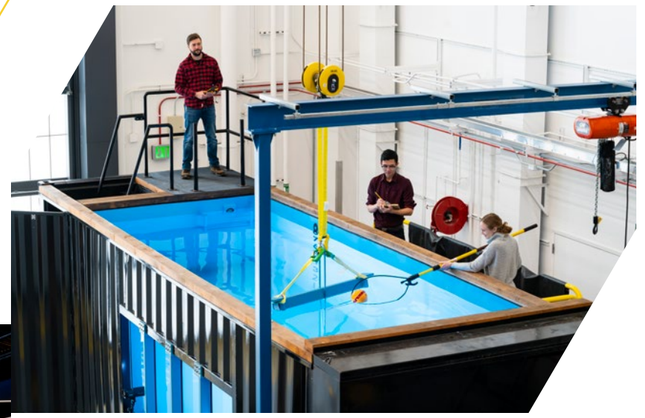
Making critical contributions requires taking risks and running experiments — work that is best done in labs. Here are some of APL's notable research and collaboration spaces.

## ADVANCED COMBAT SYSTEMS LABORATORY (ACSL)

The ACSL is a versatile, multifunctional 7,000-square-foot facility that brings engineers, analysts and warfighters together to visualize and solve complex command and control problems. The size of the facility enables realistic multi-team representation and collaboration in large military operations around the globe. The facility includes high performance computing resources that can access extensive databases and modeling and simulation capabilities, as well as external, global networks that support development of software for DOD cloud computing and timely responses to warfighter requests. Specialized equipment is installed for optimizing human-machine interaction and for human-machine teaming research.

## TRANSPORTATION SYSTEMS CENTRAL

Transportation Systems Central is a facility outfitted to enable cyber evaluation of a wide range of vehicles. The lab is a unique combination of mechanic shop and cyber evaluation lab, allowing engineers to test the cybersecurity of the software, hardware and communications on modern commercial and military vehicles. It is equipped with a variety of capabilities, including vehicle lifts, a dynamometer and links to the Laboratory's tools and resources.

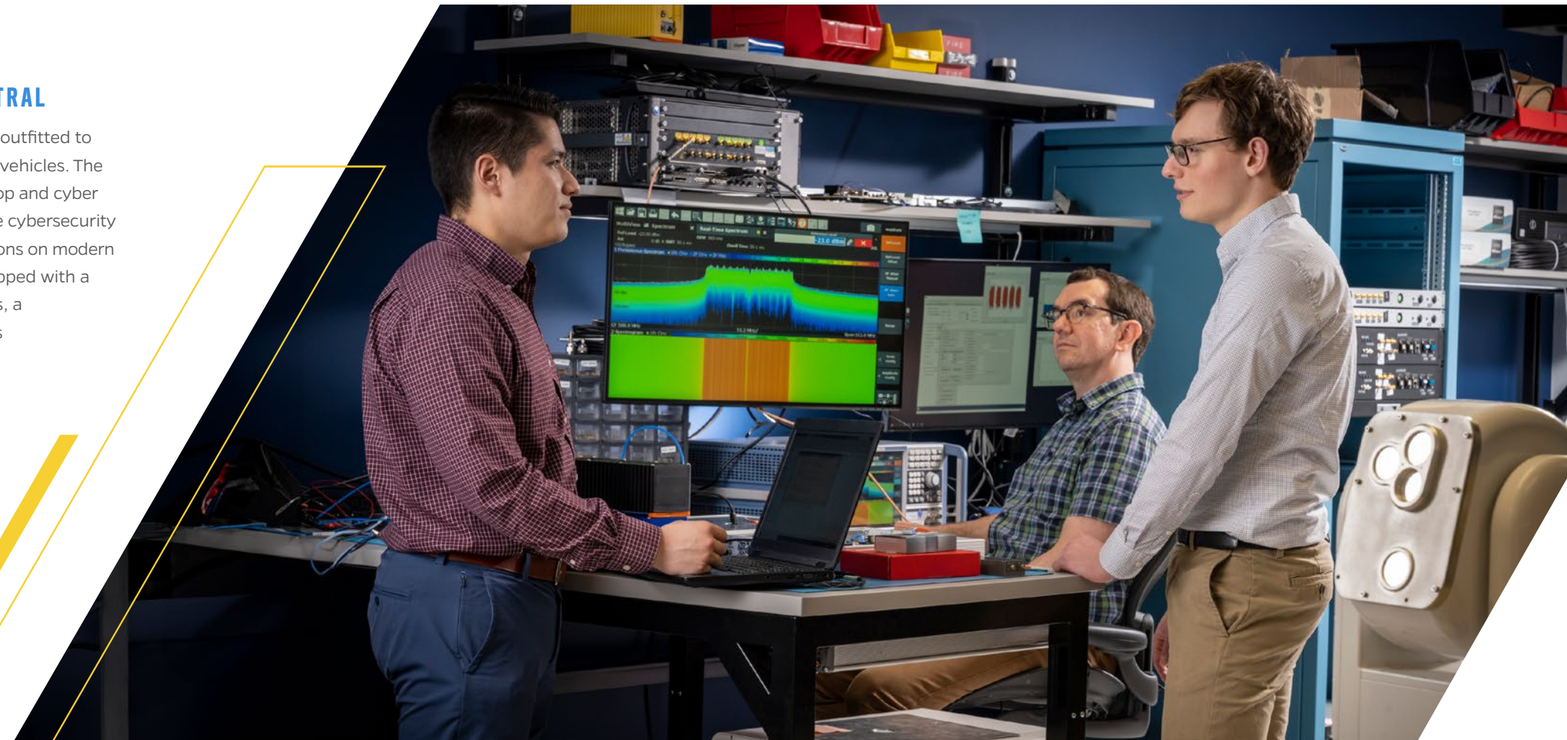


## FORCE PROJECTION SECTOR SYSTEMS DEVELOPMENT BRANCH HIGH BAY

This 4,000-square-foot climate-controlled space is used for active project support, such as fabrication, assembly/disassembly, equipment testing, maintenance and field test preparation. Large systems — like buoys, boats and autonomous vehicles — are tested in this space. It is equipped with a 20-ton overhead crane that runs along the 81-foot length of the space and provides a lift up to the 780-square-foot mezzanine with roll-up doors on the second floor. The space also houses a 20-foot saltwater test tank, providing engineers the ability to conduct testing for sea-based sensors, modeling and more.

## INTELLIGENT RESILIENT INTERNETWORKED SYSTEM (IRIS) LABORATORY

The IRIS Lab brings together experts from across APL to address challenges in providing cognitive secure, resilient communications in heterogeneous networks of networks. IRIS combines communications and networking infrastructure and knowledge ranging from the physical layer to the application layer, algorithm development using new artificial intelligence/machine learning techniques and systems integration expertise that is necessary for this new technology to be fielded to the warfighter. This integrated hardware and software development lab houses a number of test and measurement tools in both radio frequency and optical spectra, software-defined radios, communications link hardware and more. The 18-screen monitor setup has been used to support networked demos across campus, with the IRIS Lab serving as the command and control center.




## INTELLIGENT SYSTEMS CENTER (ISC)

Intelligent systems are agents that have the ability to perceive their environment, decide upon a course of action, act within a framework of acceptable actions and team with humans and other agents to accomplish a human-specified mission. The ISC leverages APL's broad expertise across national security, space exploration and health to fundamentally advance the employment of these systems for our nation's critical challenges. The ISC fosters new partnerships, both inside and outside of the Lab, hosts key projects and technologies for the enterprise and acts as the steward of the Lab's artificial intelligence strategy.


## DRAGONFLY FLIGHT LABORATORY

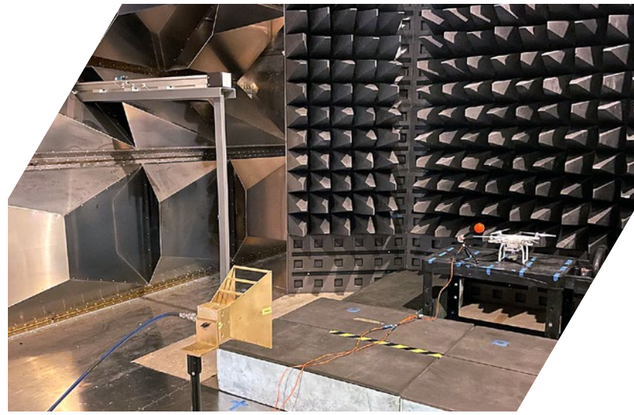
In the Dragonfly Flight Laboratory, engineers are developing the flight control system and navigation algorithms for NASA's revolutionary Dragonfly rotorcraft-lander mission to Saturn's moon Titan. The indoor facility has a 900-square-foot flight area for testing, integration and maintenance of two half-scale Dragonfly flight vehicles and a thrust test stand used to evaluate motor and propeller performance. Dragonfly marks the first time NASA will fly a rotorcraft for primary science on another world.

## MICROWAVE DIGITAL ARRAY LAB AND ANECHOIC CHAMBER

These laboratories allow for the development and testing of new technologies associated with advanced shipboard electronic warfare, radar and phased array-based communications. The anechoic chamber houses a near-field range with a 6-foot by 6-foot planar scanner and is used for continued development of APL's digital array technology for radar, electronic warfare and communications. The near-field range facility is a critical phased array antenna testing and characterization resource across multiple APL programs and sectors.

## FACILITY FOR EMP AND RF DIRECTED ENERGY (FEARDE)

High-power microwave (HPM) weapon systems use very high-power pulses of electromagnetic energy to disrupt or damage electrical systems, and our adversaries are fielding HPM weapons that are quickly becoming a threat to U.S. military assets. FEARDE is dedicated to evaluating the susceptibility of electrical components and systems to HPM signals and offers three large test chambers to support HPM projects. The facility is also equipped with a full suite of specialized RF test equipment, including high-power amplifiers, electric field and magnetic field probes, complex signal generators, signal analyzers and wideband receivers to allow for the configuration and execution of custom test designs.



## MATERIALS FOR EXTREME ENVIRONMENTS LABORATORY

APL develops mission-critical systems for such extreme environments as hypersonic flight, space exploration and deep-sea operation — where heat, pressure, oxidization, corrosion and other factors challenge the survivability of even the toughest systems. In the Materials for Extreme Environments Laboratory, innovative formulations and processing techniques, as well as unique testing, are used to enhance material performance and survivability — and create mission-engineered materials to enable critical capabilities.

## LIVE DATA, INTEGRATION, VALIDATION AND EXPERIMENTATION (LIVE) LAB

The LIVE Lab allows researchers to visualize data on information networks and use automated pattern recognition to discover anomalies that indicate cyberattacks. LIVE Lab features a suite of tools to help cyber operators detect, understand and respond to cyberattacks across many platforms and applications.

## PLANT AND ENVIRONMENTAL TESTING (PET) LAB

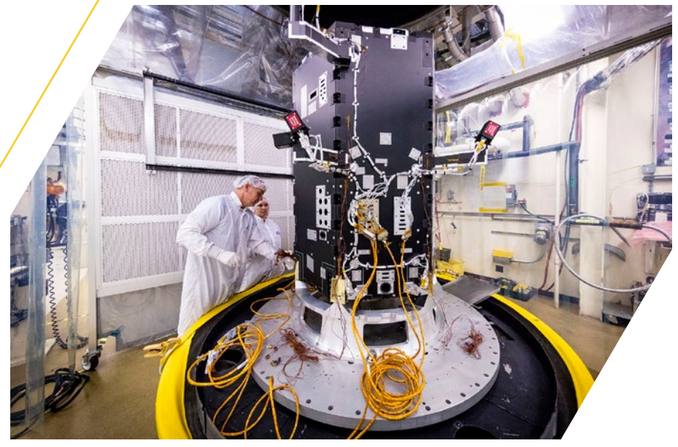
The PET Lab allows researchers to create multiple unique, isolated environments by programming lighting, temperature and humidity to mimic real-world conditions and to grow a diverse array of plants, including model organisms, crops, invasive species, aquatic plants and algae. The facility enables novel research on plant technologies, as well as climate change mitigation and food security — all areas of growing concern for APL sponsors. It has been approved by the Defense Counterintelligence and Security Agency as a classified area.


## COMBAT SYSTEMS CYBER WARFARE ANALYSIS LABORATORY (CSCWAL)

This laboratory provides a stand-alone classified environment for the development, integration and testing of cyber capabilities to support air and missile defense systems. The lab serves as the primary space for testing cyber effects, evaluating and validating cyber vulnerabilities, and developing cyber defense systems against nation-state adversaries. Because of the unique nature of CSCWAL and the array of capabilities available, APL has been able to provide several significant contributions to our sponsors.

## THE EXPERIMENTAL COMMUNICATIONS LABORATORY

This laboratory is dedicated to the development and testing of radio frequency (RF) transceiver systems and devices for signal collection applications. Equipped with signal distribution capabilities, signal analyzers, RF signal isolation capabilities, electrostatic discharge laboratory benches, multiple soldering stations and stand-alone local area networks, the facility also features several temperature chambers and spaces for hardware prototype assembly and for testing large pod-based transceiver systems.



## SPACE SIMULATION AND VIBRATION TEST LABORATORIES

The Space Simulation Laboratory replicates the operating conditions of space, and engineers use the Vibration Test Laboratory to perform structural qualification testing to ensure space systems can withstand the rigors of launch. APL's testing philosophy — test as you fly, fly as you test — has enabled the remarkable longevity of the Lab's spacecraft and instruments.

# TECH TRANSFER

Tech Transfer ensures the broadest possible impact of APL innovation — enhancing the reach of some of our ideas and technologies while promoting and protecting APL intellectual property (IP) that was developed to address the nation's most critical challenges.

An artistic rendering of the High-Rate Delay Tolerant Networking protocol being used to transfer radio and optical communications between Earth and space. It leverages NASA's Interplanetary Overlay Network, which APL has customized for broader accessibility and use. Credit: NASA

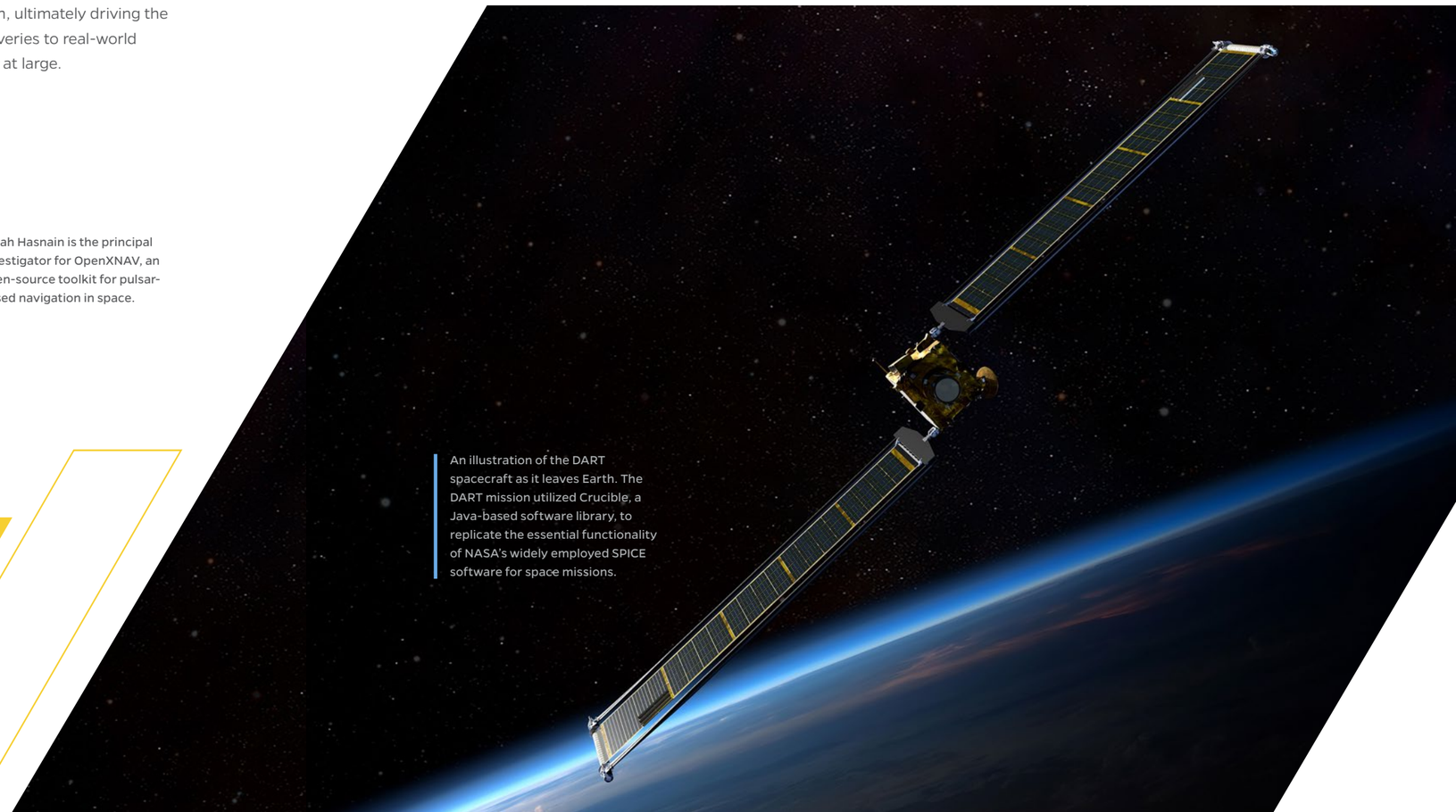
## SUSTAINING OPEN-SOURCE INNOVATION

The concept of open science — the commitment to making research outcomes and methods accessible to everyone — is critical to technology transfer efforts. It promotes transparency, collaboration and accessibility, and it facilitates the seamless exchange of scientific knowledge, data and innovations among researchers, institutions and the broader community. Open science not only accelerates the dissemination of cutting-edge technologies but also fosters innovation, encourages collaboration and expedites the practical application of research, ultimately driving the efficient transfer of scientific discoveries to real-world applications and benefiting society at large.


Sarah Hasnain is the principal investigator for OpenXNAV, an open-source toolkit for pulsar-based navigation in space.

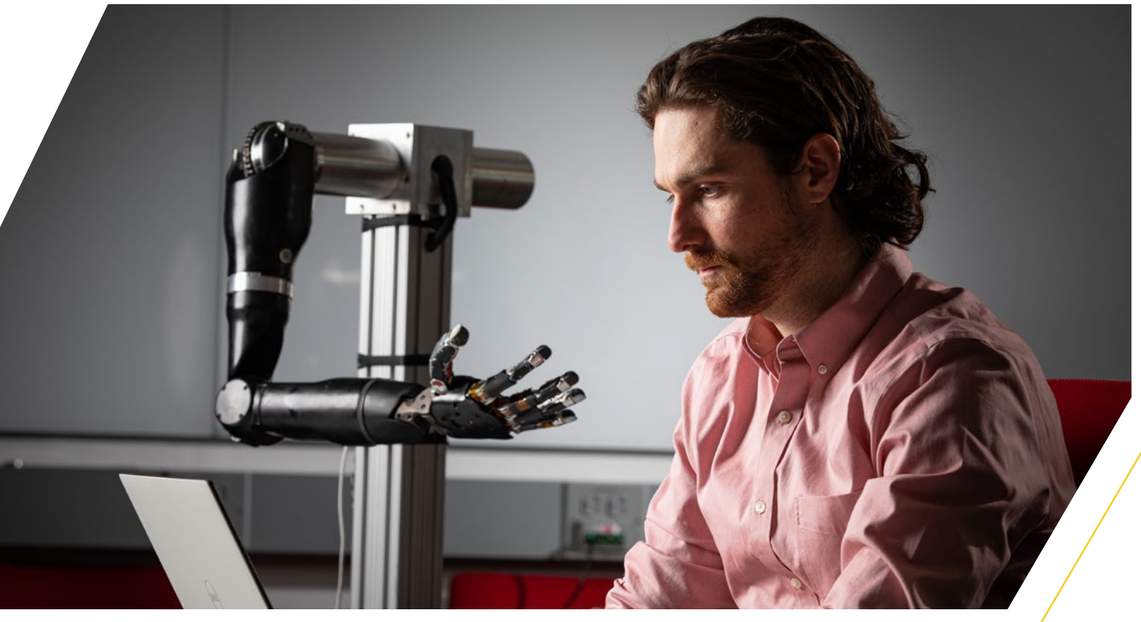
The White House designated 2023 the Year of Open Science, and many of the Laboratory's government sponsors — including NASA — published their plans to provide free access to taxpayer-funded research results. Seizing upon the opportunity, APL's Tech Transfer office, with support from the Laboratory's Space Exploration Sector, hosted a Space Open Source Challenge to develop an existing space-related software or hardware project to a state that would be suitable for open-source release. From scores of entries, a panel of judges comprising subject-matter experts from APL and the New Space community — the emerging commercial space industry — selected three winning ideas. The selected teams received up to $25,000 to develop their ideas through the remainder of fiscal year (FY) 2023. Below are the three winning submissions:

- APL is collaborating with NASA to standardize autonomous network management by creating an open-source library and sample agent. Researchers have customized the NASA Interplanetary Overlay Network (ION) for small, high-rate embedded devices, aiming to remove all NASA dependencies for broader accessibility and use.
- OpenXNAV is an innovative software-hardware testbed focused on pulsar-based autonomous navigation (XNAV) for cislunar and deep space missions. The project aims to advance this tool for public release, providing a versatile toolkit for various applications.
- APL researchers have developed Crucible, a Java-based software library. Crucible is entirely platform-independent. The team plans to release Crucible as a self-contained package for broader use. The Cassini, Double Asteroid Redirection Test (DART), Parker Solar Probe and Mini-RF missions have already benefited from Crucible.



An illustration of the DART spacecraft as it leaves Earth. The DART mission utilized Crucible, a Java-based software library, to replicate the essential functionality of NASA's widely employed SPICE software for space missions.

## IP DISCLOSURES, AGREEMENTS AND START-UPS



Luke Osborn, a senior researcher in APL's Research and Exploratory Development Department, is helping to lead studies that analyze how amputees are deploying APL's state-of-the-art, highly customizable Modular Prosthetic Limb.

In 2023, APL submitted 467 IP disclosures and entered into 69 new licenses and other agreements. A few of the more notable Tech Transfer agreements include the following:

**MindX/Blackrock.** Blackrock Microsystems, Inc., completed its acquisition of MindX Corporation, an APL start-up company, in 2023. MindX licensed APL's suite of brain–computer interface IP through two licenses executed in 2018 and 2019.

**EXOForce.** APL granted a royalty-bearing license to EXOForce Robotics Inc. for a suite of APL inventions directed at technologies that integrate sensors and computational capabilities into physical wearable garments. EXOForce aims to commercialize soft robotics, digital textiles, sensors and wearables for professional and consumer athletics and medical or consumer applications based on the APL-licensed IP.

**Phantom Neuro.** Phantom Neuro Inc., with an APL license granted in 2023, intends to develop and commercialize prosthetic limbs and assistive exoskeletons, with a focus on the needs of upper-limb amputees. The royalty-bearing license enables APL's seminal work under the Revolutionizing Prosthetics 2009 program for the Defense Advanced Research Projects Agency (DARPA) to be realized for the benefit of those in need of state-of-the-art restorative prosthetic limbs.

**BullFrog AI.** In 2018 and 2022, APL granted BullFrog AI Inc. a royalty-bearing license for select APL artificial intelligence (AI) and machine learning (ML) innovations in drug discovery. BullFrog AI recently secured more than $8 million in an initial public offering, boosting its market capitalization to over $15 million. APL previously held a 5% equity stake in BullFrog AI. The raised funds will support bringing to market APL's licensed AI/ML platforms, which were originally developed for DARPA and the Office of Naval Research and have been integrated with APL's Minotaur track monitoring tool.

## NOTABLE COLLABORATION: BLASTING THROUGH FRONTIERS

APL's Tech Transfer, in close collaboration with Johns Hopkins Technology Ventures (JHTV), devised a strategy to support Baltimore's economic revival, called "Blasting Through Frontiers." This initiative aims to stimulate APL's entrepreneurial ventures, enhance Tech Transfer cooperation with JHTV and facilitate business growth in Baltimore. The goal is to double the number of new APL start-up companies within three years. Starting in fiscal year (FY) 2024, APL procurement will implement various measures to increase Baltimore businesses' awareness of APL procurement opportunities.

Baltimore, Maryland, skyline.

## INVENTION RECOGNITION

Awarded in 2023, the Laboratory's 2022 Invention of the Year went to Will Coon for the invention STARS: System to Augment Restorative Sleep. This invention presents a novel method that transforms complex setups and direct clinician interaction during sleep disorder monitoring into an easy-to-use wearable device with automatic pattern recognition. In addition to enhancing monitoring effectiveness and efficiency in a hospital setting, the solution makes at-home monitoring possible.

Will Coon, a sleep scientist and neural signals engineer in the Research and Exploratory Development Department, explores how the brain processes information during different sleep states.

## STATISTICALLY SPEAKING — FY 2023 DATA FOR TECH TRANSFER

**467** IP assets disclosed

**20** U.S. patents issued

**132** U.S. patent applications filed*

**69** Licensing and other agreements

*Including 34 nonprovisional patent applications

# UNIVERSITY COLLABORATIONS

As the nation's largest university affiliated research center and a division of Johns Hopkins University (JHU), APL partners with other Hopkins divisions to solve some of the toughest challenges facing our world. These cross-university initiatives tap into expertise from across many fields to respond to urgent challenges — from climate change, to pandemic preparedness, to assuring autonomy.

The initiatives provide growing opportunities for APL staff to engage with divisions across Johns Hopkins, lower barriers to collaboration, foster new relationships and increase joint mission-driven research. These interdisciplinary partnerships include the Johns Hopkins Hospital, the School of Medicine, the Whiting School of Engineering (WSE), the Krieger School of Arts and Sciences, the Nitze School of Advanced International Studies, the Bloomberg School of Public Health and the Carey Business School.

## ARTIFICIAL INTELLIGENCE AND ASSURED AUTONOMY

APL and WSE have teamed up to ensure that artificial intelligence (AI) and autonomous systems throughout society are safe, secure, reliable and ethical. As smart devices, cars, homes, offices and cities proliferate, the partnership is working to drive a future in which these technologies are trustworthy contributors to society.

Run jointly by APL and WSE, the Institute for Assured Autonomy (IAA) is a national center of excellence developing tools and methodologies to widely benefit research and applications across disciplines. IAA leverages APL's and WSE's deep expertise to create strategic collaborations with external partners, creating important feedback loops between fundamental research and real-world applications. In the fast-moving field of AI, APL staff members inform research so that it is rapidly deployed to address sponsor challenges.

Building on IAA's research, APL is helping government sponsors address priorities for autonomy and intelligent systems. For instance, APL is working with the Department of the Navy (DoN) to develop its science and technology plan for intelligent autonomous systems as well as developing a naval autonomy road map that will inform the DoN's strategic investment priorities moving forward.

(From left) Research Director David Silberberg, Executive Director Jim Bellingham, and Co-Director Anton Dahbura lead the Johns Hopkins Institute for Assured Autonomy, run jointly by APL and the Johns Hopkins Whiting School of Engineering.

IAA's role is critical because if autonomy technology is not trusted, it will not be used. To create assurance, the IAA is establishing a set of tools and processes to help developers through the life cycle of their technology. Because autonomy research spans many domains, the tools developed must be generalizable and tailorable since each technology and application has unique needs.

Over the past year, APL and WSE also partnered to address the challenge of having an AI system self-assess its performance in real time. Specifically, the team developed tools that help an AI system determine whether the real-world context it encounters is similar enough to the data the AI system was trained on to be able to produce accurate results.

Most recently, IAA researchers completed 10 research projects to transform the technology sector. The two-year projects span a range of practical applications, including developing a policy framework for autonomous vehicles; developing software for safe traffic management in national airspace; assuring safe operations of AI-enabled systems in offices, hospitals and other social spaces; assuring privacy and fairness in AI technologies; and strengthening AI systems against adversarial attacks.

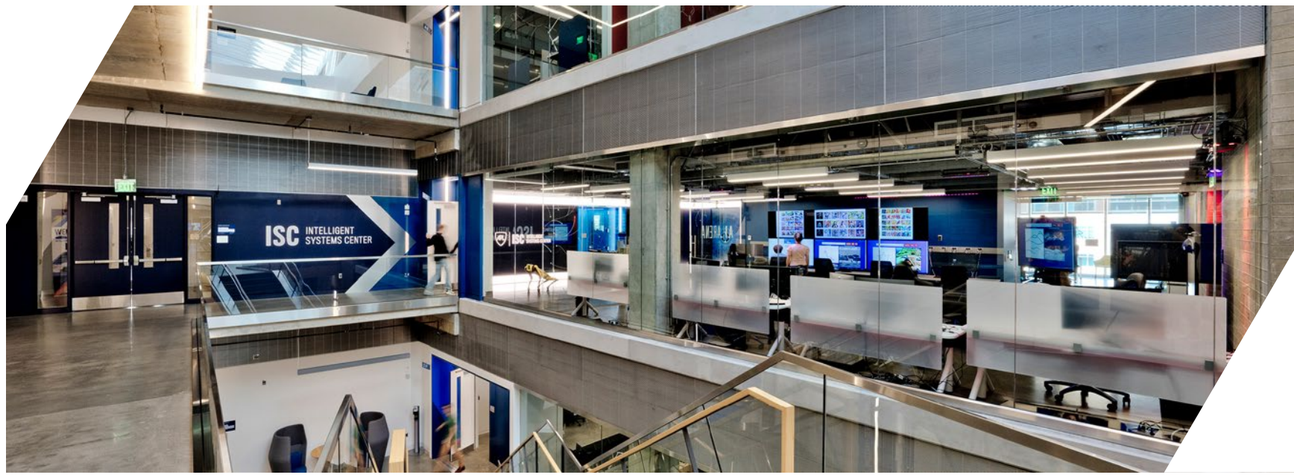
Through its funded research projects, IAA has released 50 publications and secured 14 externally funded proposals. With 25 co-principal investigators, IAA pulls from a diverse range of expertise across 12 JHU departments and five APL sectors and departments.

Building on its long-standing expertise in AI, Johns Hopkins launched the AI-X Foundry in 2023 — a critical step toward the creation of the future Johns Hopkins data science and AI institute. The AI-X Foundry establishes an organizational framework and support infrastructure for AI and data science efforts across Hopkins institutions, and its research focuses on the foundations of AI as well as the domains of health and medicine, safety and assurance, and discovery and inquiry.

The new data science and AI institute will bring together experts from a wide range of disciplines to harness emerging applications, explore new opportunities and meet the challenges presented by the explosion of data and rapid rise of accessible AI. APL will collaborate with several JHU programs on the new institute, including WSE, the Institute for Data Intensive Engineering and Science, the Bloomberg Center for Government Excellence, the Malone Center for Engineering in Healthcare and the Center for Language and Speech Processing.

The new institute will focus on the application, understanding, collection and risks of data and the development of machine learning and AI systems across a range of fields.

APL plays a key role in the framework and leadership of the AI-X Foundry and the new data science initiative. James Bellingham, a JHU Bloomberg Distinguished Professor and senior adviser in APL's Asymmetric Operations Sector, is the director of research, safety and assurance.




APL's Intelligent Systems Center is a focal point for research and development in artificial intelligence, robotics and neuroscience at APL. It houses the Institute for Assured Autonomy and JHU's new data science and AI institute.

## SURPASS

APL and WSE have partnered to enable groundbreaking solutions to ostensibly insurmountable challenges. The initiative, named SURPASS, pairs teams across institutions to tackle society's seemingly impossible challenges.

SURPASS leverages WSE's and APL's unique technical strengths and research and development communities, supporting cross-divisional teams dedicated to using innovative, multidisciplinary approaches to solve some of the world's most pressing problems. The program also pulls in experts from across JHU, including the university's School of Medicine and Bloomberg School of Public Health.

The four winning projects — BEAST: Between Earth and Space, the Next Strategic Flight Regime; CEREBRO: Enabling the Next Step of Human Evolution; Organoid Intelligence: Synthetic Biological AI; and Photoacoustic Retinal Prosthesis — are taking innovative approaches to challenges in flight, brain health, AI and vision, respectively. Each project is led by two principal investigators, one from APL and the other from WSE. Significant research for each project was conducted in 2023, and the projects will conclude in June 2024.

The team behind **BEAST** envisions a future where sustained flight in the upper stratosphere is not only possible but commonplace. To achieve this lofty goal, the team detailed a three-pronged approach focused on vehicle lift and maneuverability, which will require state-of-the-art modeling of hypersonic flow and turbulence, enhanced thrust, and thermal transport and morphing.


The **CEREBRO** team's goals are to make noninvasive brain scans readily available so they may become as common as routine checkups. The team envisions a future where a data pool may help doctors and scientists unlock the mysteries of neurological disorders, such as Alzheimer's disease, years before onset and enable noninvasive applications from human performance monitoring to brain–computer interfacing.

The **Organoid Intelligence** researchers aim to unlock the power of biological computing as a potential capability to leapfrog the current state of AI. The team is addressing ethical challenges tied to human stem cell bioengineering.


With millions worldwide experiencing visual impairment or blindness, the **Photoacoustic Retinal Prosthesis** team is developing a wearable technology that is less invasive and potentially much higher quality than traditional surgery or electrode arrays to stimulate retinal tissue and restore functional vision. The work seeks to fundamentally advance prosthetic vision.



## DISCOVERY AWARDS

Hopkins launched the Discovery Awards program in 2015 to encourage cross-university collaborations that lead to impactful work. All teams include members from at least two schools or affiliates of the university. In 2023, five research teams featuring APL investigators earned Discovery Awards. The 35 total winning project teams, chosen by faculty members from 191 proposals, feature individuals representing 10 Johns Hopkins entities. APL researchers are working on projects to help locked-in syndrome patients communicate, to restore the conduction path of the heart's electrical signals, to strengthen clean energy supply chains, to address overconfidence errors in modern AI models and to explore the gap between sensational discourse surrounding cyber-attacks and their actual impact on national security.


Dr. Nathan Crone, left, a Johns Hopkins Medicine neurologist, is collaborating with APL's Han Yi, a cognitive neuroscientist specializing in the neural basis of spoken communication, on a Discovery Award project that could help patients who are unable to move or communicate.

## HEMI

The Hopkins Extreme Materials Institute (HEMI) and APL have partnered to promote pioneering research and collaboration, awarding two $50,000 seed grants. The winning proposals — Towards Proton Radiation-Resistant Perovskite Solar Cell Materials for Space Applications, and Developing a Multiscale/Multiphysics Framework to Support the Eco-friendly Mitigation of Ice Loss From the Arctic and Greenland Glaciers and Icesheets — were each led by two principal investigators, one from APL and one from Hopkins.

Researchers on the solar cell project are looking to understand the defects that are formed when energetic particles interact with metal halide perovskites, as these can lead to performance degradation and limit the viability of promising solar cells. Their low cost, light weight and simple manufacturing process make these cells an ideal candidate for in-space manufacturing during future space missions. The team for the ice loss mitigation project is creating a mechanistic-based multiscale computational framework that can predict the mechanics of ice deformation under creep loading, as well as the effect of ice nucleation proteins on the structure and mechanical properties of ice. The study could result in an environmentally friendly framework for mitigating ice mass loss in Greenland and Antarctica.

(From left) Bart Paulhamus, Ben Rodriguez and Jim Spall.

## ENGINEERING FOR PROFESSIONALS

APL collaborates with WSE to lead graduate programs through the Johns Hopkins Engineering for Professionals (EP) program. APL continues to play a critical role in the development of programs at EP, which has its origins as an in-house program for the advanced training of APL employees.

WSE recently selected two APL staff members as EP program chairs. Bart Paulhamus, chief of APL's Intelligent Systems Center, was named chair of the Whiting School EP AI program. Ben Rodriguez, an experienced data science researcher, was named co-chair of EP's data science program, sharing leadership of the program with APL staff member Jim Spall.

The online master's program in AI is one of the nation's first. The curriculum explores AI areas such as computer vision, machine learning, robotics, natural language processing and advanced algorithms. The program is designed to prepare engineers to take advantage of opportunities in this field, with a team of top-level researchers, scientists and engineers guiding students through rigorous online academic courses.

The online master's degree program in data science is designed to address the growing demand for data scientists to serve as knowledgeable resources in our ever-evolving data-driven world. Students will engage in a number of modern online courses covering topics such as machine learning, data visualization, game theory and large-scale data systems in order to expand their knowledge for advanced career opportunities in data science.

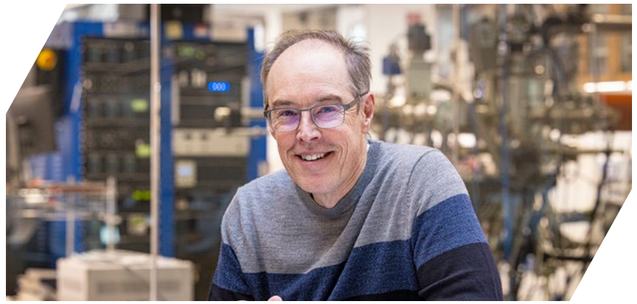
EP offers online and part-time master's degrees and certificates in more than 22 program areas, 13 of which are chaired by APL staff members.

# A CULTURE OF INNOVATION

From incubating bold research proposals and developing the next generation of leaders to building collaborative workspaces, APL fuels creativity and new ideas at every level.

To help our staff members come together and push the boundaries of what's possible, APL supports the exploration of great ideas through its robust system of grants and collaboration initiatives. Efforts over the past several years to make innovation grants and workspaces more accessible to staff members from every corner of the Laboratory have paid off with a surge in engagement. In 2023, several of these initiatives saw a marked increase in proposals and competition.

But APL is not resting on its laurels. We continue to embrace the idea that the next game-changing concept could come from anyplace — or anyone — at the Laboratory by developing grants for operations and business solutions, which also play key roles in enabling innovations for our sponsors.



Joseph Miragliotta, 2023 Master Inventor, was recently recognized for a career marked by innovation with more than 10 patents based on APL intellectual property. He actively leverages the Laboratory's Independent Research and Development (IRAD) program, participating in five projects in fiscal 2023.


## IRAD

The Independent Research and Development (IRAD) program is an innovation cornerstone at APL. Every year, each of the Lab's mission areas embarks on a search for research and development projects to meet future sponsor needs. Calls for IRAD proposals identify critical national problems that have yet to be solved and whose solutions have the power to produce breakthroughs.

In 2023, several mission areas reported an unprecedented response to their IRAD calls for proposals, indicating continued growth in engagement across the Laboratory. IRAD projects are selected for funding annually by mission area leadership on the basis of the research's relevance to their particular domains. Leaning into APL's technical competencies, staff members investigate national defense capabilities through basic and applied research, system and concept formulation studies, and development. IRAD projects often mature into technologies or contributions that successfully address ongoing sponsor challenges.

Technical sectors often host events to highlight projects funded through APL's IRAD program. Staff members peruse projects at an Asymmetric Operations Sector poster session (top) and a Space Exploration Sector symposium (bottom).

## OPERATIONS AND BUSINESS INNOVATION (OBI) ACCELERATOR AND AWARDS PROGRAM

Behind the Laboratory's bold and game-changing technical innovations are hundreds of operations and business staff members who are constantly growing APL's processes and workflows to enable critical work in support of our sponsors.

The Enterprise Business Committee at the Laboratory launched the OBI program in 2022 to acknowledge, foster and reward these efforts. In 2023, the team posed its first challenge to solicit ideas for future initiatives in the operations and business community, and APL staff members from nearly every department and sector submitted a total of 56 ideas to the challenge. Labwide voting helped to select three winning ideas with the potential to provide significant value to APL business and operations processes. The winning teams received funding to bring their ideas to life over the course of 10 weeks.

Angie Sutton, left, and Jessica Chase led the successful launch of APL's Operations and Business Innovation program, acknowledging the business and operations community's efforts to enhance daily workflows and support APL's missions.

## BLAST

When the Laboratory recognized a need years ago to specifically develop early-career staff members in innovation practices, the BLAST program — short for Building Leaders, Accelerating Science and Technology — was born. BLAST offers early-career and new-to-APL staff members, from any sector or department, the opportunity to tackle a challenging technical problem relevant to APL's sponsors.

Each summer, BLAST participants work in several teams on a technical problem and develop a demo-ready solution by the end of August. Teams present their solutions to a panel of judges, and a winner and runners-up are selected. Before the challenge is announced, participants are grouped with teammates with whom they have not previously worked and who bring different skill sets and backgrounds to the table. Delaying announcement of the challenge topic encourages the creation of diverse teams.

During the challenge, early-career staff members learn how to manage a project and budget from start to finish. Participants also expand their peer networks and develop relationships with senior staff members, who serve in advisory roles and as judges at the end of the BLAST cycle. In 2023, the teams focused on supply chain resilience and restoration, developing capabilities to mitigate supply chain disruption, specifically related to manufacturing.

Additionally, more than half the teams who participated in BLAST's fiscal year 2022 cycle on cislunar safety successfully transitioned their work to Project Catalyst grants or IRAD projects to continue developing their innovations.


The 2023 winning team for the Building Leaders, Accelerating Science & Technology (BLAST) program — (from left) Sabrina Lesser, Haley Whitham, Mit Patel, Nicholas Knowlton and Elliot Ressler — developed a Mobile Modular Medical On-Demand Device (M3D2), which provides a point-of-care response to supply chain disruptions for critical patient care products.

> **“In Will’s case, the first idea didn’t move forward, but he took the initiative to transition those insights into an Ignition Grant.”**

**— Erin Conroy,** Innovation & Collaboration Project Manager

## PROJECT CATALYST

Project Catalyst is a Labwide grant program comprising three internal funding opportunities for APL staff members. These grants advance high-risk, transformative ideas that can run from initial hypothesis explorations to significant research and development — and, perhaps, the next APL Defining Innovation.

- **Ignition Grants** are awarded to solutions for a themed challenge and encourage initial hypothesis testing. Teams post their proposals online for review by their peers. A Labwide crowdsourced voting process and panel of challenge representatives then determine the winners.
- **Combustion Grants** fund visionary ideas that advance the current state of the art and show promise for solving a sponsor’s challenge. APL peer reviewers and a panel of technical leaders select the winning proposals.
- **Propulsion Grants** support the search for game-changing solutions to critical challenges that have yet to be solved through conventional methods. The high-risk, high-reward proposals can span multiple years, with recipients competing to earn subsequent funding.

Innovations developed through Project Catalyst grants often take a winding road before they obtain sponsor funding. Luckily, there are a number of avenues at the Laboratory to find internal funding to continue developing a potentially game-changing idea, whether through other Project Catalyst opportunities or through IRAD projects.

“The more authors discuss and refine their ideas with others, the better the idea becomes,” said Erin Conroy, a project manager for APL’s Innovation & Collaboration Program. “Frequently, a team will submit a proposal that isn’t selected the first or second time, but when they keep adjusting it to be bolder and more revolutionary, that’s when the idea is awarded funding.”

Will Stone, a molecular biologist in APL’s Research and Exploratory Development Department, ultimately received funding from the Defense Advanced Research Projects Agency (DARPA) to develop an emergency food source from microbes (read more on page 38). But the idea began as a Propulsion Grant to grow multispecies biofilms to support life on Mars. When the idea failed to receive second-year funding, Stone was not deterred. He connected with Rickey Egan, who works in the Lab’s Asymmetric Operations Sector, and they were awarded an Ignition Grant to bring the idea down to Earth, producing a sports-drink-like beverage out of microbes to provide hunger relief in a disaster area or in the event of a supply chain disruption.

As the Ignition Grant finished, DARPA put out a call for its Cornucopia program, which invited proposals to develop capabilities for field-deployable, on-demand production of a range of nutritious, palatable foodstuffs from engineered microbes, air, water and electricity. Stone and Egan’s work was a natural fit.

“Will and his team aimed to tackle a really hard, ambitious problem up front,” Conroy said. “The hardest problem is where the real technical risk is. With Project Catalyst grants, we want to see new learning. In Will’s case, the first idea didn’t move forward, but he took the initiative to transition those insights into an Ignition Grant.”

Will Stone leveraged a Propulsion Grant and an Ignition Grant to genetically engineer microbes to help humans survive in extreme environments.

## JANNEY GRANTS

APL’s Janney Grants initiative, reimagined in 2022, provides a pathway to support staff members interested in external engagement and thought leadership.

The program has seen a surge of interest, with total applications increasing by 26%. Enhancements to and new opportunities in the reimagined program included a streamlined funding application process, tailored mentorships to help staff members optimize their Janney awards and increased collaboration opportunities with trusted national and international partners.

In a 2023 survey of Janney recipients, 34% indicated they have used funding to attend a conference and 20% used funding to author a paper — opportunities that can lead to a broader impact for the Laboratory.

Janney Grants’ mission is to nurture a culture of discovery, embrace risk and put APL at the center of a vibrant innovation ecosystem. Janney exists to fund the “white space,” those efforts that are beyond current strategic priorities, transcend mission areas or assert APL leadership into new or nontraditional domains or venues. The grants fund externally facing thought leadership activities for staff, support them in their roles in strategic technical societies and strive to increase APL’s involvement in the global science and technology community.

APL’s Janney awards date back to 1984 and are named after Stuart Janney Jr., longtime member of the Johns Hopkins University board of trustees and APL board of managers. The program, in all its iterations, has remained steadfast in encouraging staff members to pursue new ideas in emerging technology. The program complements APL sector and department education and training funds.

## CENTRAL SPARK

Central Spark is the Laboratory’s open, collaborative space for making, tinkering and ideating. In Central Spark, staff members are free to pursue any innovation effort, whether for sponsor programs or (on their own time) personal projects.

The facility occupies a fully renovated 9,000-square-foot space and remains open around the clock and readily accessible to all staff members who wish to collaborate, create, design, prototype and take advantage of the innovation center’s sophisticated virtual reality, augmented reality, 3D printing and other capabilities. Central Spark continues to capture the attention of users within APL and has served as the launchpad for a number of inventions and concepts developed for our sponsors.

In 2022, Central Spark kicked off the Champions Program, designed to create subject-matter experts within the innovation and technology center. Champions educate APL staff on innovative capabilities, participate in the strategic direction of the space and receive VIP access to new technologies.


Staff members have the freedom to pursue any innovation effort, whether for sponsor programs or personal projects, in Central Spark.

# AWARDS AND HONORS

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2019, 2020, 2021, 2022 and 2023

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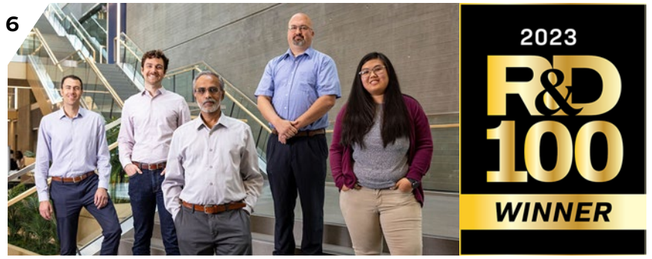


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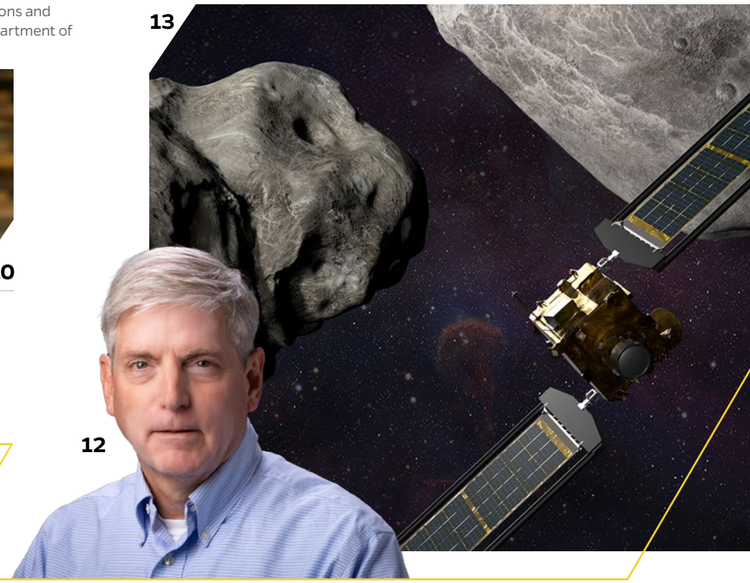

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1. For the fifth year in a row, Fast Company featured APL on its Best Workplaces for Innovators list. APL is one of only two companies to make the list every year since the award's inception in 2019. The Lab placed 17th among a list of the top 100 innovative companies from around the world. Additionally, the Laboratory was selected for the Best Workplace for Innovators award in the early-career category.

2. For the sixth consecutive year, APL placed in the top 25 of Foundry's Computerworld Best Places to Work in IT list, which recognizes the top worldwide workplaces for information technology (IT) professionals. The Laboratory was ranked No. 23 overall among large organizations and No. 5 on the IT growth list, which recognizes organizations that excel in mentoring programs, training budget, promotions within IT, accessibility of training to remote employees and unique training programs.

3. For the second consecutive year, APL was honored with a Glassdoor Employees' Choice Award as one of the top 100 Best Places to Work among large U.S. companies. APL ranked No. 42 on the list, marking the second year in a row that the Laboratory has been in the top 50.

4. Two of APL's technology breakthroughs were honored with Fast Company's 2023 World Changing Ideas Awards. The Double Asteroid Redirection Test (DART) mission was named the winner in the experimental category, while the Laboratory's per- and polyfluoroalkyl substances (PFAS) filtration and destruction methodology was recognized as one of eight finalists in the water category.

5. For the second year in a row, APL won a Handshake Early Talent Award. Given to just 180 out of more than 750,000 companies that use the Handshake website, the award recognizes employers of choice for Generation Z job seekers.

6. APL's Wearable Thin-Film Thermoelectric Cooling (TFTEC) Device for Prosthetics and Haptics was named as a 2023 R&D 100 Awards winner as one of the top 100 revolutionary technologies in the world. Pictured are APLers who received a patent for the Fast-Rate Thermoelectric Device: (from left) Bobby Armiger, Luke Osborn, Rama Venkatasubramanian, Jonathan Pierce and Meiyong Himmtann. Another APL-developed technology—a suite of machine-learning algorithms named Prometheus, Euclid and Seagull—was named a finalist in that same category.

7. Senior Fellow James Gosler (left) received the 2022 Eugene G. Fubini Award in recognition of his significant contributions and sustained outstanding service as an adviser to the Department of Defense (DoD). The award is the highest honor conferred by the Secretary of Defense to a civilian who has significantly contributed to the mission of the DoD through national-level defense studies and task forces. Credit: U.S. Army/Pfc. Brandon Perry

8. Five APL staff members, (from left) Malcolm Taylor, Gill Brown, Jamie Porter, Nicole Brown and Camille Daniel, received Black Engineer of the Year Awards. Daniel received the Capt. Donnie Cochran Legacy Award, Taylor was named a Modern-Day Technology Leader, and N. Brown, G. Brown and Porter were each recognized with a Science Spectrum Trailblazers Award.

9. Nelli Mosavi-Hoyer, project manager for NASA's EZIE and Van Allen Probes missions, was recognized with Women in Aerospace's 2023 Aerospace Awareness Award for her leadership and outreach efforts.

10. Lee Rogers, chief engineer of the Sea Control Mission Area, received the Bronze Medal Award for Technical Achievement in Undersea Warfare at the National Defense Industrial Association's 2023 Undersea Warfare Fall Conference.

11. Jon Ward (left), Kevin Fahrer (not pictured) and Matthew Sharp received awards from the Association of Old Crows (AOC) for their work promoting the development of electronic warfare (EW) capabilities for the U.S. military.

12. Ed Reynolds was named to the 2023 TIME 100 list of most influential people in recognition of his role leading the DART mission. The TIME 100 list recognizes artists, innovators, leaders, icons and pioneers from around the globe who are changing the world.

13. DART was recognized with the American Institute of Aeronautics and Astronautics' (AIAA) newest award—the AIAA Award for Aerospace Excellence—for marking "humanity's first time purposely changing the motion of a celestial object by a team of protectors of our home planet." The mission also earned the National Space Club and Foundation's Nelson P. Jackson Aerospace Award, which honors the previous year's most outstanding contribution to the missile, aircraft or space field. In addition, the DART team received the 2023 Space Achievement Award, a top award from the Space Foundation that recognizes individuals or organizations that have demonstrated breakthrough space technology or program success representing milestones in space exploration.


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**14.** Seven members of the DART team—mission systems engineer Elena Adams, the late mission operations manager Ray Harvey, project manager Ed Reynolds, deputy project manager Caitlin Shearer, and co-investigators Mallory DeCoster, Dawn Graninger and Emma Rainey—had asteroids named in their honor.

**15.** The Communications Department received several social media and digital video awards for their work on the DART mission, including a gold honor in Government & Politics at the 15th Annual Shorty Awards and three Telly Awards, which honor excellence in video and television across all screens.

**16.** Team members on NASA's Europa Clipper mission picked up two NASA awards honoring their accomplishments building and delivering the spacecraft's propulsion module. The Europa Clipper Module team was presented with the Group Achievement Award, and Stuart Hill (pictured) was recognized with an Exceptional Public Achievement Medal.

**17.** Dave Jansing, an engineer who has made significant contributions to APL's work in remote sensing to address critical technology challenges in national defense, was named the 2023 Out to Innovate LGBTQ+ Engineer of the Year.

**18.** (From left) Tania Díaz Márquez, Mayra Amezcua, David Díaz Márquez and Teresa Johnson were honored with Johns Hopkins Diversity Leadership Council Diversity Recognition Awards. Johnson was recognized for bringing awareness to the valuable contributions neurodiverse and physically disabled people make to create innovative and diverse solutions for APL and its sponsors, while D. Díaz Márquez, T. Díaz Márquez and Amezcua shared the award as the executive committee for ¡HOLA!, the Laboratory's Hispanic and Latinx Culture Club.

**19.** Jeff Boye was named the 2023 Outstanding Young Engineer by the Maryland Academy of Sciences. Credit: Maryland Science Center

**20.** The APL Achievement Awards ceremony celebrated 753 staff members nominated in 144 entries for 25 different categories. Ultimately, 168 staff members were recognized for 31 winning entries.

**21.** Richard "Dickie" George, one of the world's foremost code-breaking mathematicians, was recognized by the National Security Agency with his induction into the National Cryptologic Hall of Honor.

**22.** Joseph Mulé (right) was presented with the Missile Defense Agency's prestigious 2023 Aegis Ballistic Missile Defense (BMD) Pathfinder Award, in recognition of his outstanding contributions to the nation's missile defense programs. Credit: Aegis BMD Program Office

**23.** Andy Newman (left), who leads a team of more than 70 APL scientists, mathematicians and engineers in cutting-edge development and implementation of advanced data fusion and sensor resource management capabilities, was presented with the Joe Mignogna Data Fusion Award, which honors a leader in the data fusion community. Credit: Military Sensing Symposia

**24.** NASA presented its Group Achievement Award to the Parker Solar Probe team team, lauding the team's novel engineering, which has enabled the spacecraft to collect nearly three times as much data as required and has led to unanticipated discoveries. The award was accepted by Parker Project Scientist Nour Rawafi (left).

**25.** NASA's Solar System Exploration Research Virtual Institute (SSERVI) presented its Angioletta Coradini Award to planetary geologist Brett Denevi. The award honors a midcareer scientist for broad and lasting accomplishments in a SSERVI research field.

**26.** Shelby Wilson (left) and Michelle Chen were recognized with 2023 Women of Color STEM awards. Chen received the Outstanding Technical Contribution award, and Wilson received the Technology Rising Star award.

**27.** Tao Jen (left) and Rubbel Kumar received awards from the Society of Asian Scientists and Engineers (SASE). Jen was named SASE's Engineer/Scientist of the Year (Government), and Kumar received a SASE Promising Professional award.

**28.** APL's George Clark (left) and Barry Mauk were honored with prestigious NASA Honor Awards for their distinguished contributions and service to NASA's Juno mission to Jupiter and the agency's mission overall. Clark received an Early Career Achievement Medal, and Mauk received NASA's Exceptional Public Service Medal.

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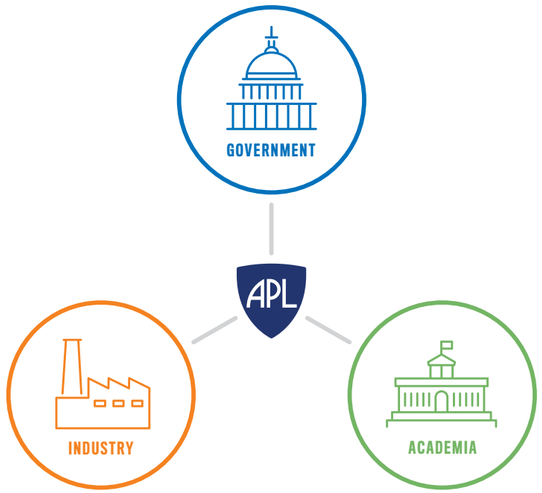
# ABOUT UARCS

University affiliated research centers (UARCs) "are not-for-profit entities sponsored and primarily funded by the U.S. government to address technical needs that cannot be met as effectively by existing government or contractor resources. These organizations typically assist government agencies with scientific research and development, studies and analyses, and systems engineering and integration by bringing together the expertise of government, industry, and academia to solve complex technical problems in the public interest."

**—Department of Defense UARC Engagement Guide**




## OUR LONG-TERM STRATEGIC RELATIONSHIPS WITH SPONSORS ARE CHARACTERIZED BY:

- Responsiveness to evolving sponsor requirements
- Comprehensive knowledge of sponsor requirements and problems
- Broad access to information
- Broad corporate knowledge
- Independence and objectivity
- Quick response capability
- Current operational experience
- Freedom from real or perceived conflicts of interest

## APL IS A UARC AND A RESEARCH DIVISION OF JOHNS HOPKINS UNIVERSITY

This is a relationship we hold dear and one that helps to enable our objective and independent work.

While we have strict conflict-of-interest restrictions, our sponsors can include government offices and philanthropic organizations.

UARCs function broadly as trusted technical experts, often developing advanced system prototypes that accelerate the infusion of new technology into operational use. When appropriate, and where no conflict of interest exists, they may compete for science and technology work on Broad Agency Announcements and Announcements of Opportunity.

The majority of our work comes from the Department of Defense as sole-source (noncompetitive) funding under the Competition in Contracting Act, primarily through the exception for essential research and engineering.





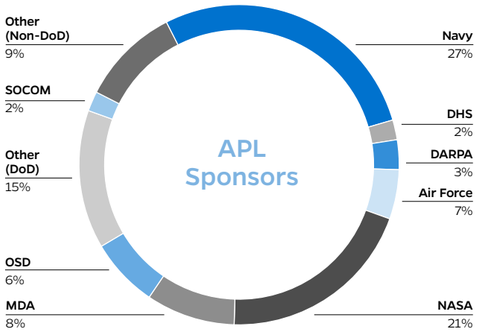
APL CORE COMPETENCIES

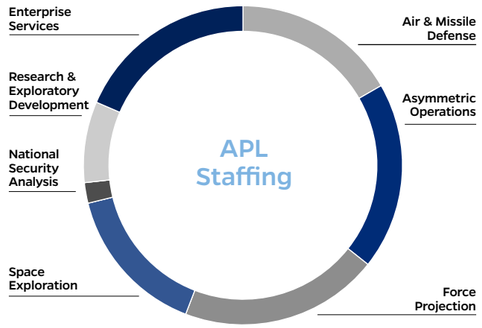



# FINANCE AND STAFFING

During the fiscal year that ended September 30, 2023, the Johns Hopkins Applied Physics Laboratory recorded revenue from contracts and grants totaling $2.33 billion. As a scientific and educational nonprofit organization, we reinvest proceeds from our contract research and development activities into programs, facilities and capabilities that further our scientific and technology development mission.

## FY23 Revenue: $2.33 Billion




### APL'S GOAL IS TO CREATE DEFINING INNOVATIONS THAT ENSURE OUR NATION'S PREEMINENCE IN THE 21ST CENTURY

**Our success as a UARC depends on:**

- Broad exposure to challenges facing a wide variety of sponsors
- A diversity and depth of expertise and experience to address those challenges
- Our track record of bringing together government, academia and industry to solve complex challenges

### OUR ACCESS TO NUMEROUS INNOVATION ECOSYSTEMS HELPS US IN OUR WORK

**In 2023, we had:**

- 152 different government sponsors
- 102 subcontracts to 43 different universities



## APL FIELD OFFICES

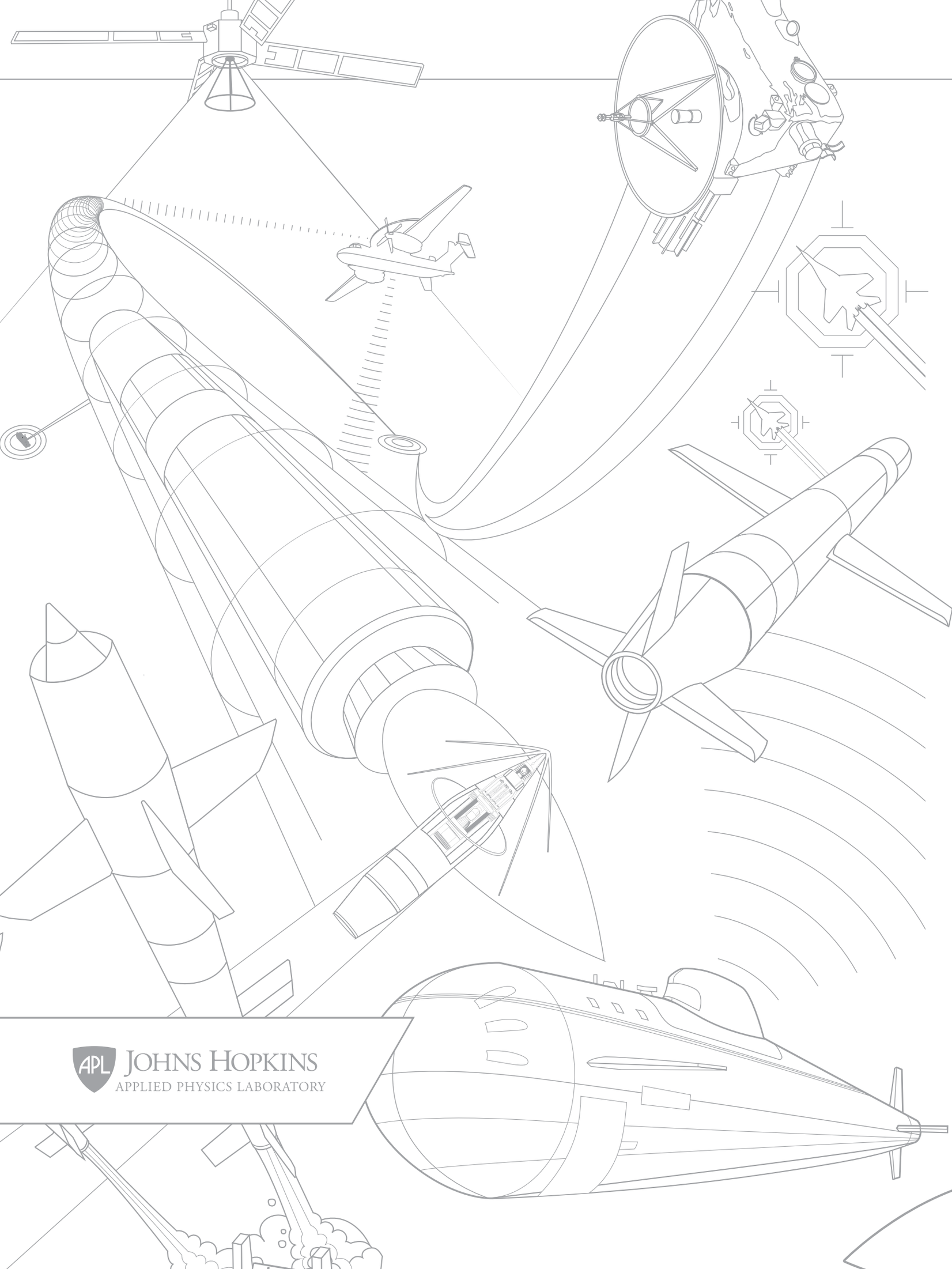
**Colorado Springs**
565 Space Center Drive
Suite 135
Colorado Springs, CO 80915

**Fort Walton Beach/ Eglin Air Force Base**
73 Eglin Parkway NE
Fort Walton Beach, FL 32548

**Hill Air Force Base**
6002 Wardleigh Road
Suite 202
Hill AFB, UT 84056

**Lexington Park**
46579 Expedition Drive
Suite 300
Lexington Park, MD 20653

**National Security Space Los Angeles**
400 Continental Boulevard
Suite 310
El Segundo, CA 90245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