# ANNUAL REPORT

# 2021

THE JOHNS HOPKINS APPLIED PHYSICS LABORATORY

# APL: A UNIVERSITY AFFILIATED RESEARCH CENTER

University affiliated research centers (UARCs) are independent, nonprofit organizations that conduct essential research, development and systems engineering to strengthen our nation. The centers focus on strategic national priorities, free from conflicts of interest or competition with commercial industry. They provide the U.S. government with access to highly skilled scientists, engineers and analysts to tackle vital national security and scientific challenges.

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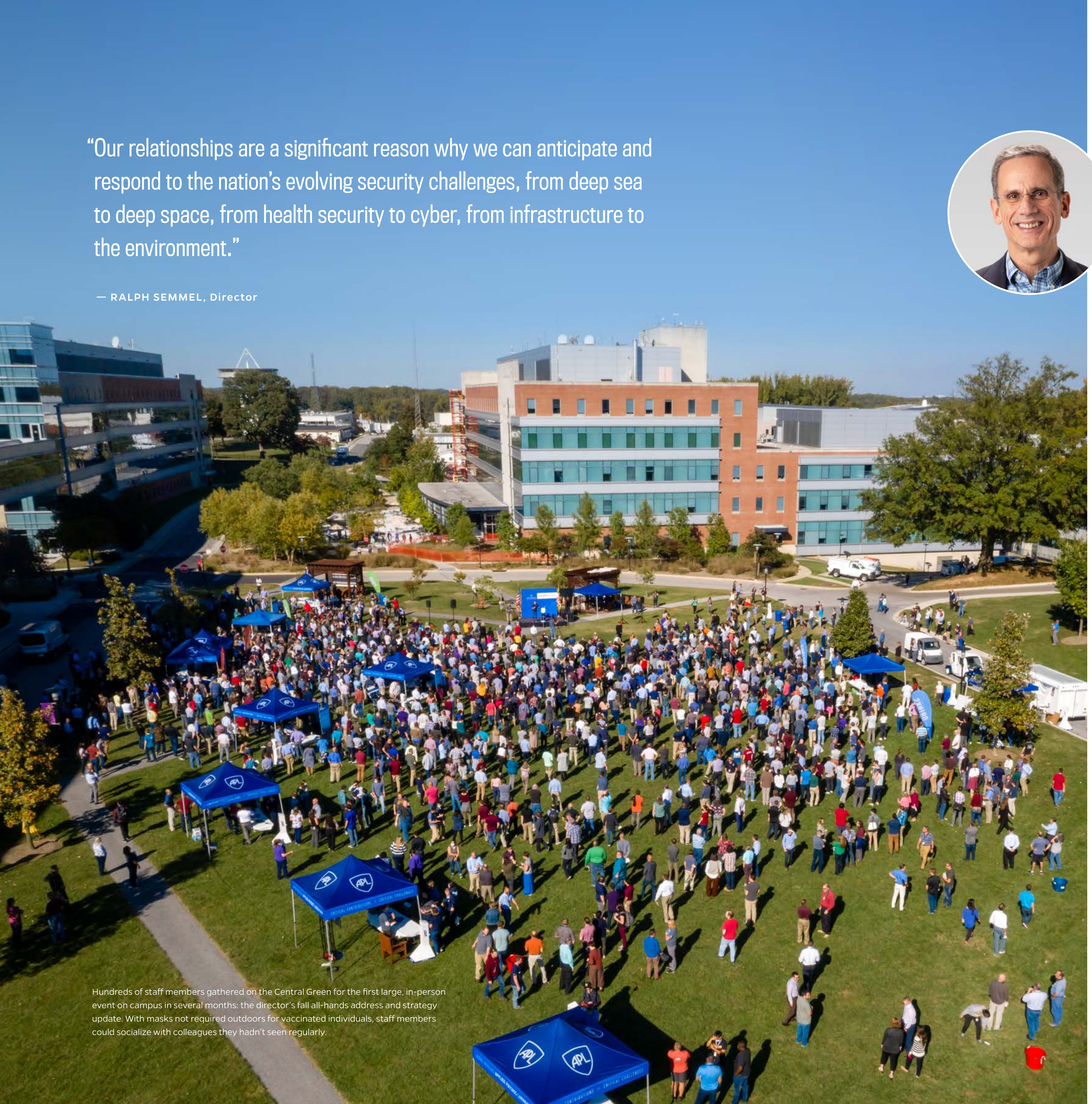
“Our relationships are a significant reason why we can anticipate and respond to the nation’s evolving security challenges, from deep sea to deep space, from health security to cyber, from infrastructure to the environment.”

— RALPH SEMMEL, Director



Hundreds of staff members gathered on the Central Green for the first large, in-person event on campus in several months: the director’s fall all-hands address and strategy update. With masks not required outdoors for vaccinated individuals, staff members could socialize with colleagues they hadn’t seen regularly.

# DIRECTOR’S MESSAGE

As I look back at the accomplishments of the past year, I am filled with deep gratitude for my colleagues—for their dedication, their optimism and their singular focus to push the boundaries of innovation for our sponsors and those we serve.

For nearly eight decades, a community of passionate people at the Applied Physics Laboratory have taken on the nation’s most difficult technical problems. From deep sea to deep space, from national security to exploration of the cosmos, from cyber operations to health care and the environment, we join together to make critical contributions to many of the critical challenges facing our nation.

2021 was indeed an impressive year for APL, especially in light of the struggles so many had to overcome during the pandemic. This report reflects our staff’s relentless commitment to mission, world-class technical expertise and collective willingness to take on challenges that many thought were impossible.

The Laboratory positioned itself in new ways to serve the many sponsors who depend on us, while enabling staff members to balance health and family needs. I was continually inspired by the creativity and resilience of my colleagues under incredibly difficult circumstances. Ever mindful of the challenges our nation faces and APL’s essential role, we did not slow down.

In fact, we made history on several fronts. We launched the world’s first planetary defense test mission, NASA’s Double Asteroid Redirection Test. Parker Solar Probe “touched” the Sun. APL innovations accelerated development of a new class of autonomy-enabled defense systems and set cybersecurity standards for control systems used by industry and for national security. Our teams created new capabilities for prosthetic limbs and pushed the limits of what is possible in artificial intelligence, quantum computing and novel materials. As you will see in this report, there were indeed many stunning achievements.

As I enter my second decade as director of APL, I am as proud of my colleagues and friends as I have ever been. Their achievements, ingenuity and determination are contributing every day to the well-being of our nation and leading to a safer and better world.

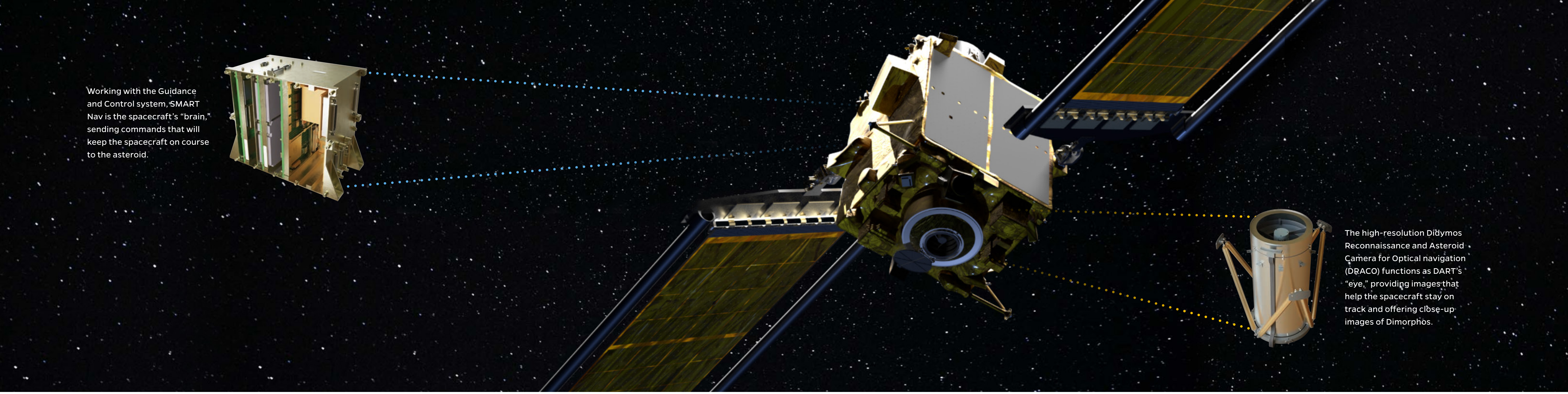
Ralph Semmel

# PUSHING THE BOUNDARIES OF BOLD INNOVATION

At APL, our culture of taking bold risks, brought to life through inventive prototyping and informed by deep technical expertise, is the basis for our efforts to not merely anticipate the future, but create it.

In 2021, APL innovations enabled the world's first-ever planetary defense mission, accelerated the development of a new class of autonomy-enabled weaponry, created a standard for cybersecurity for industrial control systems, raised the bar for what a person can do with a prosthetic limb and pointed the way to a potentially break-through technology: working quantum sensors.

NASA's Double Asteroid Redirection Test (DART) spacecraft sets off to collide with an asteroid in the world's first full-scale planetary defense test mission. Riding atop a SpaceX Falcon 9 rocket, DART launched on Nov. 24, 2021, from Vandenberg Space Force Base in California. (Credit: NASA/Johns Hopkins APL/Ed Whitman)



Working with the Guidance and Control system, SMART Nav is the spacecraft's "brain," sending commands that will keep the spacecraft on course to the asteroid.

The high-resolution Didymos Reconnaissance and Asteroid Camera for Optical navigation (DRACO) functions as DART's "eye," providing images that help the spacecraft stay on track and offering close-up images of Dimorphos.

## ASTEROID-SMASHING AUTONOMY

Lighting up the California coastline early in the morning of Nov. 24, a SpaceX Falcon 9 rocket launched NASA's Double Asteroid Redirection Test (DART) on its one-way trip to crash into an asteroid.

DART — a mission designed, developed and managed by APL for NASA's Planetary Defense Coordination Office — is the world's first full-scale test of technology for defending Earth against potential asteroid or comet hazards.

APL's contributions to DART span mission and investigation planning and design, systems engineering, instrument development — specifically, the Didymos Reconnaissance and Asteroid Camera for Optical navigation (DRACO), technically the only instrument onboard DART — and the building and installation of individual spacecraft components. But the Lab's most innovative contribution is the software that will guide DART to its target. SMART Nav — short for Small-body Maneuvering Autonomous Real-Time Navigation — is a set of computational algorithms that will steer DART during the last four hours of its existence.

SMART Nav is responsible for seeing DART through a stretch of some 54,000 to 62,000 miles and ensuring that it collides with its target, Dimorphos, millions of miles away from Earth. Dimorphos — the moonlet of the Didymos binary asteroid system and a rock of unknown shape, with a diameter of about 520 feet — will be barely visible to DART until the last hour or so before impact, at which point it will resolve into a small, faint and blurry blob. At that distance, remote control is not an option.

To successfully navigate under those constraints, SMART Nav has to make precise, deliberate decisions about whether, when and where to maneuver. To that end, the SMART Nav algorithms employ several advanced techniques: extrapolating from faint blobs of light to identify Didymos and Dimorphos, isolating Dimorphos and tracking its position relative to DART's trajectory, and determining how to stay on a collision course with the tiny moonlet while burning the least possible amount of fuel.

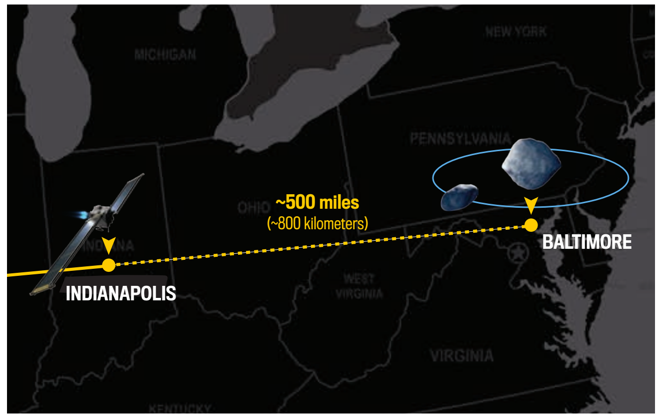
Andy Cheng, an APL planetary scientist and one of the DART investigation leads, reacts after the successful launch of the DART spacecraft. Cheng, who came up with the idea for DART, watched the launch from the Mission Operations Center on APL's Laurel, Maryland, campus.

> "With SMART Nav, it's no longer about just keeping the spacecraft in a prescribed orientation or carrying out correction maneuvers. It's about conducting the last four hours of the mission without any human intervention."
>
> — **MARK JENSENIUS, DART Guidance, Navigation and Control Engineer**

SMART Nav will repeat that process about once a second for the duration of DART's final approach, ceasing only a couple of minutes before collision, at which point the spacecraft will coast for more than 500 miles at about 4 miles per second (or 14,400 miles per hour) until impact. APL has conducted nearly 20,000 simulations of those crucial four hours, accounting for a wide range of possible asteroid shapes and light-refraction scenarios.

SMART Nav's impact will reverberate well beyond DART's historic collision with Dimorphos, anticipated for fall 2022. According to Michelle Chen, the SMART Nav lead at APL, the algorithms can be applied to any mission that is bandwidth-limited, as well as any mission involving small bodies where there is little or no prior information.

Beyond that, SMART Nav may well serve as a template for future space missions that require increasingly capable autonomy to cover ever-greater distances.




The SMART Nav system will automatically guide DART to its target, setting up a final coast equal to leaving the starting line at Indianapolis Motor Speedway and gliding into Baltimore's Camden Yards.


Together, the Golden Horde program and its Operation Protovision competition offered a virtual place for innovators to gather and develop technology.

## AUTONOMOUS WEAPONS, ACCELERATED BY AI

Space is not the only domain in which the Lab is pushing the limits of autonomous algorithms. In collaboration with the Air Force Research Laboratory (AFRL), APL is accelerating the development of artificial intelligence (AI) capable of guiding a new kind of weapons system — known as networked, collaborative and autonomous (NCA) — that observes and reacts to the dynamics of the battlespace in real time.

In 2021, APL built a simulation environment to support Operation Protovision, a competition sponsored by AFRL, as part of its Golden Horde program, in which teams of so-called Gladiators compete in a virtual Colosseum to create the most effective NCA weapon system in response to a stressing challenge problem.

Building on APL's 2020 success in creating a competition environment for the Defense Advanced Research Projects Agency AlphaDogfight trials, in which an AI bested an experienced F-16 fighter pilot in a simulated dogfight, APL brought its considerable experience in AI, machine learning and reinforcement learning to bear in support of the competition. However, building a virtual environment for NCA weapons systems is a great deal more challenging and complex than building one for individual fighter jets.

"The challenge problem is a stressing scenario against a regional air defense system," explained APL mathematician and physicist Robert Shearer. "It contains both long- and short-range missile defense systems, as well as early warning radars and jamming systems, all split into sectors under control by a sector commander."

Alongside APL engineer Steven VanDerwalker, Shearer developed this representative air-to-ground strike scenario in AFRL's Advanced Framework for Simulation, Integration and Modeling, fine-tuning it to be as close to the real world as possible.

The opening competition of Operation Protovision took place in December. The Colosseum and the broader competition orchestration framework "performed admirably," said Brandon Coloe, an APL guidance, navigation and control systems engineer and the project's technical lead. As intended, the Colosseum enabled rapid integration of the Gladiators' intelligent weapon concepts, executing and processing nearly 500 simulations over a three-day span.

Like SMART Nav, the Colosseum and associated technologies will influence future research and development as the needs of the nation require more complex and rigorous, yet flexible and collaborative, virtual environments to accelerate development of autonomous capabilities.

## COMPREHENSIVE ICS CYBER DEFENSE

To develop the Colosseum, APL had to integrate an array of disparate capabilities from a diverse range of organizations. That same challenge is at the heart of MOSAICS — from More Situational Awareness for Industrial Control Systems — the first-ever comprehensive, integrated and automated solution for industrial control system (ICS) cybersecurity. ICSs are critical to the delivery of electricity, water, fuel and other assets crucial to our society.

Cyber threats to ICSs may not be quite as cinematic as Earth-bound asteroids or cruise missiles, but what they lack in flash they make up for with alarming ubiquity. As demonstrated by a series of headline-grabbing hacks affecting SolarWinds, the Colonial Pipeline and the Oldsmar water treatment facility, ICSs are more vulnerable than ever to cyberattacks. Existing cyber defense for these systems consists of ad hoc, piecemeal solutions that lack the sophistication to keep up with modern vectors of attack.

The military is not immune to these threats. APL is leading the ongoing development of the MOSAICS capability, in partnership with Sandia, Pacific Northwest and Idaho National Laboratories. Although MOSAICS was originally envisioned as a system for detecting cyberattacks on ICSs, APL leveraged its expertise in systems engineering and ongoing work in Integrative Adaptive Cyber Defense (IACD) to develop a true ICS operational defense capability, one that allows ICS operators to detect and characterize cyberattacks on their systems in real time, and will eventually support automated — and even autonomous — response and recovery protocols.

The U.S. Navy conducted a military utility assessment in August, deploying the system at Naval Facilities Southwest in San Diego, California. Over five days, MOSAICS surveilled a 3,000-node network while 17 adversarial attacks were launched against a simulated control station on the base. The attacks targeted every level of the system, from devices in the supervisory layer, such as servers and engineer workstations, all the way down to low-level devices like electrical relays and logic gates.

Without defensive technologies in place, the nation's water treatment facilities could be vulnerable to cyberattack.

While monitoring the entire network, MOSAICS successfully identified every attack, achieving a 100% success rate with fewer than 1% false positives. What's more, when a contractor showed up at the base unannounced and began installing new components into the electrical system without obtaining proper authorization, MOSAICS flagged the installation as a possible cyberattack, demonstrating its real-world utility.

The Navy will continue using MOSAICS for a year and is seeking funding to deploy the capability at additional bases. Harley Parkes, APL's design and development lead for MOSAICS, said that his team is working to increase the system's functionality and make it easier to learn, use and deploy.

Ray Yuan, the mission area executive for Cyber Operations at APL, said that "MOSAICS represents a major step forward from existing solutions — the transition from a haphazard and piecemeal cybersecurity approach to an all-encompassing, integrated capability that can be used in the field."

The next big step is to incorporate autonomy into the system, so that MOSAICS and other capabilities like it can take action to defend and repair ICSs without human intervention.

"MOSAICS represents a major step forward from existing solutions – the transition from a haphazard and piecemeal cybersecurity approach to an all-encompassing, integrated capability that can be used in the field."

— **RAY YUAN, Mission Area Executive, Cyber Operations**

"Because there are almost as many possible use cases for the Modular Prosthetic Limb as there are possible users, each individual trial represents another important step in furthering the technology."

— COURTNEY MORAN, Prosthetist

## MYOELECTRIC MUSIC

Many of APL's boundary-pushing innovations of 2021 are focused on performing mission-critical functions with little human intervention. But the Modular Prosthetic Limb (MPL) enables autonomy in a different sense — restoring lost abilities to human beings.

Developed by APL more than a decade ago, the Laboratory and its collaborators continue to iterate and improve on the advanced prosthetic arm — making consistent, and sometimes surprising, discoveries. In 2018, Johnny Matheny of Florida, who lost his left arm to cancer in 2007, became the first person to take it home for a full year. Researchers captured the observations and lessons learned from that trial in a 2021 article published in the Journal of Neural Engineering.

That research, along with two videos, demonstrated that Matheny had mastered the device to a surprising degree. Controlling the limb via myoelectric signals generated by his amputated arm, Matheny customized the MPL to perform complex gestures and actions, including controlling individual fingers well enough to play the piano.

Particularly surprising to the researchers was the efficiency gain Matheny made during the trial. Given that he already had extensive experience with a variety of prosthetic limbs, they did not expect to observe, as they did, that the myoelectric signals produced by Matheny to move the arm were markedly smaller and less variable over time, an indicator of efficiency gain and more effortless control.

Following the success of Matheny's trial, an additional participant brought the MPL home and used it for several months. "Because there are almost as many possible use cases for the MPL as there are possible users, each individual trial represents another important step in furthering the technology," said Courtney Moran, a certified prosthetic clinician who has worked with most of the patients involved in APL's testing and refinement of the MPL.

Luke Osborn, APL researcher and lead author of the study, said that many exciting and important challenges remain. "Understanding how prosthesis users interact with their environment, outside of the clinic or laboratory, will help lead to the design and development of more sophisticated performance measures that will be important metrics for tracking functional improvements over time."

## SIGNAL AND NOISE

Matheny's success with the MPL demonstrates the immense power that can reside in very small electrical signals. Other scientists at APL are working to unlock the vast potential of even smaller signals — those found in the quantum realm.

Quantum sensing has the potential to radically increase the power of sensing technology by enabling the detection of extremely small and low-powered signals — a breakthrough that could greatly benefit health, science, defense and other domains. But optimizing quantum sensors has proven difficult, stymied by the complexity of control schemes, or ways to stabilize a quantum system so that accurate measurements can be taken.

In 2021, researchers at APL devised an optimal control scheme for detecting very faint signals using a quantum system. In a paper published in npj Quantum Information (a Nature Portfolio journal), the team described their approach, which hinged on the insight that when detecting signals at the quantum level, raw sensitivity is less important than the signal-to-noise ratio. Many quantum control schemes have been devised for other purposes, such as detecting the magnitude or frequency of quantum signals. These schemes do benefit from high sensitivity, but the same does not apply to the problem of detecting the presence or absence of a signal.

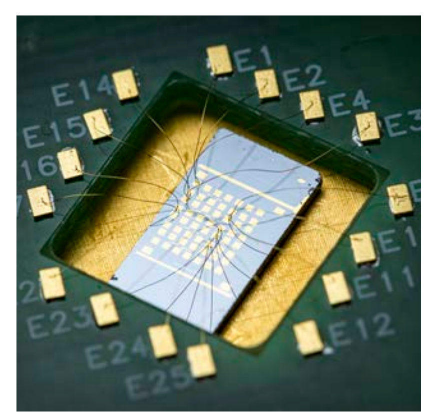
So, the team conceived of the problem differently, by asking the question of how to optimally detect the presence of a stochastic (indeterminate, or random) signal falling within a known spectrum in the presence of background noise. By taking this approach, they found the spin-locking control scheme — a simple scheme that is used in a variety of applications, from cybersecurity to nuclear magnetic resonance spectroscopy — to be the optimal solution.

The team, led by APL quantum physicist Paraj Titum, also developed a simple numerical technique to generalize their approach to apply to any situation in which a signal needs to be isolated from background noise. Their findings show that the scheme described in their paper can easily be implemented in quantum sensors developed in the near term.

APL's boundary-pushing contributions of 2021 spanned virtually every scale of scientific endeavor, from the vast vacuum of space to the subatomic realm. The Lab enabled a historic mission to the far reaches of space, accelerated autonomous algorithms to pilot advanced weaponry, created a successful prototype of tomorrow's ICS cybersecurity systems, empowered an amputee to make music with one of the most sophisticated artificial limbs ever produced and discovered a possible path to quantum sensing.

"Quantum sensing has seen a lot of recent interest through theoretical progress and impressive experimental results on a variety of platforms."

— PARAJ TITUM, Quantum Physicist



Mayra Amezcua is part of a team of APL researchers applying quantum computing capabilities to radically increase the power of sensing technologies.

# DEDICATED

## TO THE DEFENSE OF THE NATION

For 79 years, APL has developed and served as a technical resource for many of the technologies that have proven crucial for the defense of the nation. Equally as important as the technologies themselves has been the Laboratory's dedication to fostering close-knit ties to the national defense community and our keen understanding of its unique needs.

In its role as a trusted technical advisor, APL ensures that systems on the Navy's Arleigh Burke-class destroyers are able to meet evolving challenges presented by our nation's adversaries.

As a university affiliated research center, APL brings diverse teams of subject-matter experts together to tackle difficult challenges and ensure our nation's preeminence across all domains.

## A ONCE-IN-A-LIFETIME RADAR SYSTEM UPGRADE

The complexity of the multiple missions its surface combatant ships must face and the advances needed to meet exceedingly challenging environments and threats create substantial challenges for the Navy. Solving them requires transformational Integrated Air and Missile Defense capabilities, which APL has been working on with our government and industry partners. APL's long-standing history with these systems earned the Lab its technical leadership role on the collaborative SPY-6 development team, which, in 2021, delivered the new SPY-6 system for installation on the first Flight III Arleigh Burke-class destroyer, the USS Jack H. Lucas (DDG-125).

In support of the Navy and collaborating with design agent and prime contractor Raytheon, APL ensured that the first SPY-6 iteration, SPY-6(V)1, and those that follow are poised to deliver vast improvements in warfighting performance. The four-face, electronically steered phased-array radar provides significant upgrades in detection range, sensitivity and accuracy. It's also capable of supporting multimission warfare, providing defense against ballistic and cruise missiles, anti-surface and anti-air threats, and electronic warfare. Designed to integrate into existing ship hulls and combat systems, SPY-6 also allows the Navy to avoid across-the-board new ship upgrade costs and more easily transfer the technology to a future ship class.

Participating in the system upgrade is, for some at APL, actually a twice-in-a-lifetime experience. The Lab also served as technical advisor for the SPY-6 predecessor, SPY-1, which continues to serve the nation after nearly 50 years. APL's technical oversight of the SPY-6 upgrade was shaped by the Lab's decades-long involvement in naval initiatives to identify new radars based on the pace of technological development. APL was central to the "Navy Radar Roadmap," which defined the large-scale radar upgrade path for the surface Navy.

SPY-6 will soon transfer to the operational Navy as part of the Arleigh Burke-class Flight III destroyer program, and smaller variants of SPY-6 are slated for installation on new and existing ship classes, including carriers, frigates and amphibious vessels. APL will continue to oversee the integration and testing of the radar for the Aegis Combat System and Flight III destroyer ship systems until it is turned over to the Navy in 2024 as an Initial Operational Capability.

"APL is uniquely positioned to provide deep capability across the many disciplines needed to deliver something of this magnitude. It maintains a breadth and depth of technical skills needed to get the job done."

— **DON CHESLEY, Advanced Radar Chief Engineer**

The AN/SPY-6 Air and Missile Defense Radar array (right) installed on the USS Jack H. Lucas (left), the latest destroyer in the Arleigh Burke class, is the first of four SPY-6 designs in development. (Credit, from left: U.S. Navy and Raytheon)



The Long Range Discrimination Radar at Clear Space Force Station, Alaska, includes a multiface radar designed to provide search, track and discrimination capability in support of U.S. homeland defense. (Credit: MDA)

"This ballistic missile defense technology will help keep the U.S. and our allies safe from many rogue states that possess and threaten to use such weapons."

— **GERRY RICCIARDI, APL LRDR Hardware Technology Readiness Assessment Panel Team Lead**

## LONG RANGE DISCRIMINATION RADAR BOLSTERS MISSILE PROTECTION

In December, years of engineering and technical leadership by APL for the Missile Defense Agency (MDA) Ground Sensors Directorate culminated in Lockheed Martin's installation of the multimission Long Range Discrimination Radar (LRDR) at Clear Space Force Station, Alaska.

LRDR is a multimission, multiface radar capable of conducting integrated missile defense and space domain awareness (SDA) missions through a wide field of view and is a primary component of the MDA's layered defense strategy to protect the U.S. homeland from ballistic missile attacks.

LRDR tracks and discriminates against multiple threats simultaneously, sending hit assessment data to the Missile Defense System (MDS) firing units such as the Ground-based Midcourse Defense (GMD) System. LRDR combines the strengths of lower-frequency radars that excel at searching large volumes of space with higher-frequency radars that excel at determining which of the multiple objects are threats.

Once fully operational, the new radar will be more powerful and dependable than currently active radars. LRDR will monitor and identify satellites, spent rocket casings and other debris orbiting Earth, further enabling the military's threat detection capabilities.

APL's involvement with LRDR started at its inception when APL and partner organizations shared an initial set of radar concepts with MDA, followed by APL's system trade team's analysis of each concept, which allowed MDA to weigh the strengths of each system. Once a final concept was chosen, APL developed the initial set of radar requirements just four months after the LRDR contract was awarded in 2016.

APL continued its technical leadership role, working with Lockheed Martin and the government product team to meet the goals and objectives of the original reference concept. Not only will LRDR provide unparalleled surveillance abilities as soon as it passes integration and testing phases, its highly adaptable nature will enable it to address additional threats in future configurations.

"COVID-19 helped us all appreciate things we used to take for granted. While in-person events were put on pause, our developments in the undersea domain – and the progress of now near-peer competitors – were not."

— **LISA BLODGETT, Head, Force Projection Sector**

## FROM THE SURFACE OF THE SEA TO WHAT LIES BENEATH

Beneath the water's surface, APL continues to provide long-standing technical support for our nation's submarine forces. The Laboratory was involved in the Navy's first Demonstration and Shakedown Operation (DASO) in 1960 to evaluate and demonstrate the readiness of submarine strategic weapon systems critical to nuclear deterrence. Now, over 60 years later, APL supported DASO-31 for the USS Wyoming (SSBN-742), an Ohio-class ballistic missile submarine, including a successful two-missile test flight of unarmed life-extended Trident II (D5LE) missiles in September.

Over 11 weeks, APL observed, evaluated and advised the submarine's crew and closely examined the submarine's complex systems. The operation required the considerable and combined knowledge of 55 APL launcher, missile, navigation, fire control and system experts on staff. These experts worked closely — sometimes literally so in the submarine's cramped quarters — with the submarine's crew to create documentation, execute procedures and perform special tests with uncompromised attention to detail, all in a fast-paced operational environment.

Recognizing the unparalleled technical complexity and crew proficiency that enable the success of these operations, Laboratory Director Ralph Semmel and APL Board of Managers Chair Heather Murren attended and observed DASO-31. Their support came at a critical point in the course of APL's history with DASO iterations; as the cadence of DASOs continually evolves and the time between operations lengthens, transferring knowledge of these complex strategic systems to new Laboratory staff members — as APL has for decades — is more important than ever. APL is currently exploring how to leverage virtual training simulation capabilities, under development at the Laboratory, to further aid in this knowledge transfer.

Another key component of APL's ongoing efforts to maintain the highest expertise in submarine technology is our continued facilitation of the annual Submarine Technology Symposium (STS). Organized by APL and sponsored by the Naval Submarine League, STS 2021 allowed military, industry and academic leaders to gather in person from July 20 to 22. Held primarily in APL's Kossiakoff Center, the three days of events covered topics from developing and implementing technologies to theater undersea warfare, including high-end combat against the nation's near-peer competition.

APL first collaborated with the Naval Submarine League to organize the STS in 1988. The symposium was conceived as a classified forum where technologies relevant to capabilities of submarines and related systems could be examined and advanced by various experts. Today, STS is considered the premier technical conference on submarine-related technologies.

## TO THE MOON AND BACK

While the undersea domain remains a critical operational environment, the Department of Defense is expanding its focus to include the expanse between the Earth's surface and the Moon's orbit, known as cislunar space. Some accounts estimate that adversaries will be operational in this environment by 2030, making U.S. cislunar defensive capabilities vital to protecting national interests. To meet this need, APL is developing novel ways to intelligently track and navigate the predicted increase in cislunar traffic.

Chief among the technological needs is acquiring adequate traffic control imaging for cislunar space. Current imaging consists of mere blips on a screen, but as cislunar traffic increases (and more blips appear), existing technology cannot fully and accurately interpret their identity and purpose. APL is creating a generation of software that can assist human operators to clarify and analyze crowded cislunar imaging. Combined with an equally novel, scaled-up system of task sensors that can be developed and trained to capture a wide variety of cislunar activity, the network is intended to be powerful, sensitive and flexible enough to cover all of cislunar space.

Laboratory experts are also thinking through the traffic management problem from a technical perspective. "On Earth, you have thousands of aircraft, and we take for granted that they don't run into each other," said Peter Sharer, chief engineer in the National Security Space Mission Area. "From a transportation and civilian perspective, there is a security aspect to securing the air space that is true of cislunar space as well. We are working on tools and techniques to secure air space, and on tools and tech to secure deep space, too."

Any technical solution must also navigate complex cislunar physics. The effects of lunar gravity on a spacecraft are significantly different from Earth gravity, and the transition between these effects is nonlinear. Orbital transits in cislunar environments are prone to chaos — dynamic, random states of disorder — and require new computational approaches. To address these issues, APL relies on its expertise in artificial intelligence and machine learning to study and analyze vehicle performance in this environment and drive cislunar operational discoveries.

"From a transportation and civilian perspective, there is a technical aspect to securing the air space that is true of cislunar space as well."

— **PETER SHARER, Chief Engineer**

As renewed national and global emphasis on the Moon has inspired a focus on "cislunar space," APL experts are helping sponsors shape strategies and technology applications for this critical region between Earth and the lunar surface.

## HIGHLY MANEUVERABLE FIXED-WING UNMANNED AERIAL VEHICLES

The future also promises change for defense operations within Earth's atmosphere, particularly the rapid pace of unmanned aerial vehicle (UAV) development. The Defense Advanced Research Projects Agency (DARPA) OFFensive Swarm-Enabled Tactics (OFFSET) program is dedicated to envisioning how swarms of collaborative UAV systems can provide insights to ground troops operating in dense metropolitan environments. In 2021, during the program's fourth phase, APL explored a question central to the ultimate vision: Can fixed-wing UAVs retain their greater range, endurance and speed while also acquiring the agility and mobility of their quadcopter counterparts?

APL's goal was to control a fixed-wing UAV at high speeds in an urban, outdoor environment by taking multiple passes around a target building — without hitting it. To do so, the Laboratory leveraged previous, internally funded work on aerobatic maneuvers for fixed-wing UAVs, the Aerobatic Control and Collaboration for Improved Performance in Tactical Evasion and Reconnaissance (ACCPITER) technology. Then using a mesh — a virtual map — of previous DARPA field tests in urban environments, APL flew fixed-wing UAVs in this virtual environment. These tests served as the basis to develop the algorithms to control the off-the-shelf aircraft outfitted with APL-developed electronics and software.

Finally, APL took testing to real-world environments. In fierce winds, the aircraft successfully launched from approximately 100 meters away, completed two passes through the crowded urban area while maintaining three meters of space from the target building. APL then pushed the test to a 250-meter launch, where its fixed-wing UAV autonomously and successfully flew four times faster than the quadcopters around a bigger building and under an overpass, demonstrating that fixed-wing UAVs can match the agility and mobility of quadcopters while retaining their unique advantages.

APL engineer Luca Scheuer takes part in an OFFSET field test; the DARPA program is enabling a variety of swarming technologies, tactics and test environments.

## COORDINATING UNMANNED AUTONOMOUS SYSTEMS

In future military operations, unmanned autonomous vehicles will need to intelligently collaborate while teamed with manned vessels, over the horizon and in austere communications environments. In pursuit of this capability, APL is engaging with the Navy on applications of the Laboratory's "Minos" technologies, a family of APL-developed tools that support and advance manned-unmanned teaming. In 2019, APL completed the first phase of the Minos project, demonstrating manned–unmanned teaming with vessels that leveraged the Laboratory's Minotaur software, which combines and presents multiple sensor feeds on a single operating platform, and APL's Autonomy Toolkit (ATK), a lightweight, behavior-based software architecture for swarming unmanned systems that operates robustly in unreliable communications situations.

Building on the previous work, the second phase of the project increased the level of complexity, introducing conflicting mission goals, simulated beyond-line-of-sight communication and simulated over-the-horizon operations that more closely represented real-world scenarios.

Using watercraft, a ground control station and unmanned aerial vehicles, APL conducted an experiment with two Laboratory-developed autonomy technologies that enabled data gathering, coordination and decision-making for unmanned platforms amid the new challenges. The first of these technologies is the collaborative, platform-agnostic Mission Management capability, which enables multiple unmanned platforms with different autonomies to execute various missions and adjust to tactical situations without human intervention. The second, the Distributed Multi-Modal Data Fusion technology, enables collaborative decision-making among participating manned and unmanned platforms by combining and sharing information from multiple sources, including marine radars, optical sensors and electronic navigation charts.




APL brought a full range of its expertise to bear during a December workshop that examined the future of autonomous systems and their ability to transform concepts of operation. Clockwise from top left, Elena Shrestha; Anthony Tripoli, Katie Blythe, Taylor Buck, Dan Losapio, and Mike Yakovlev; Jeff Chavis; and Brendan McNelly.

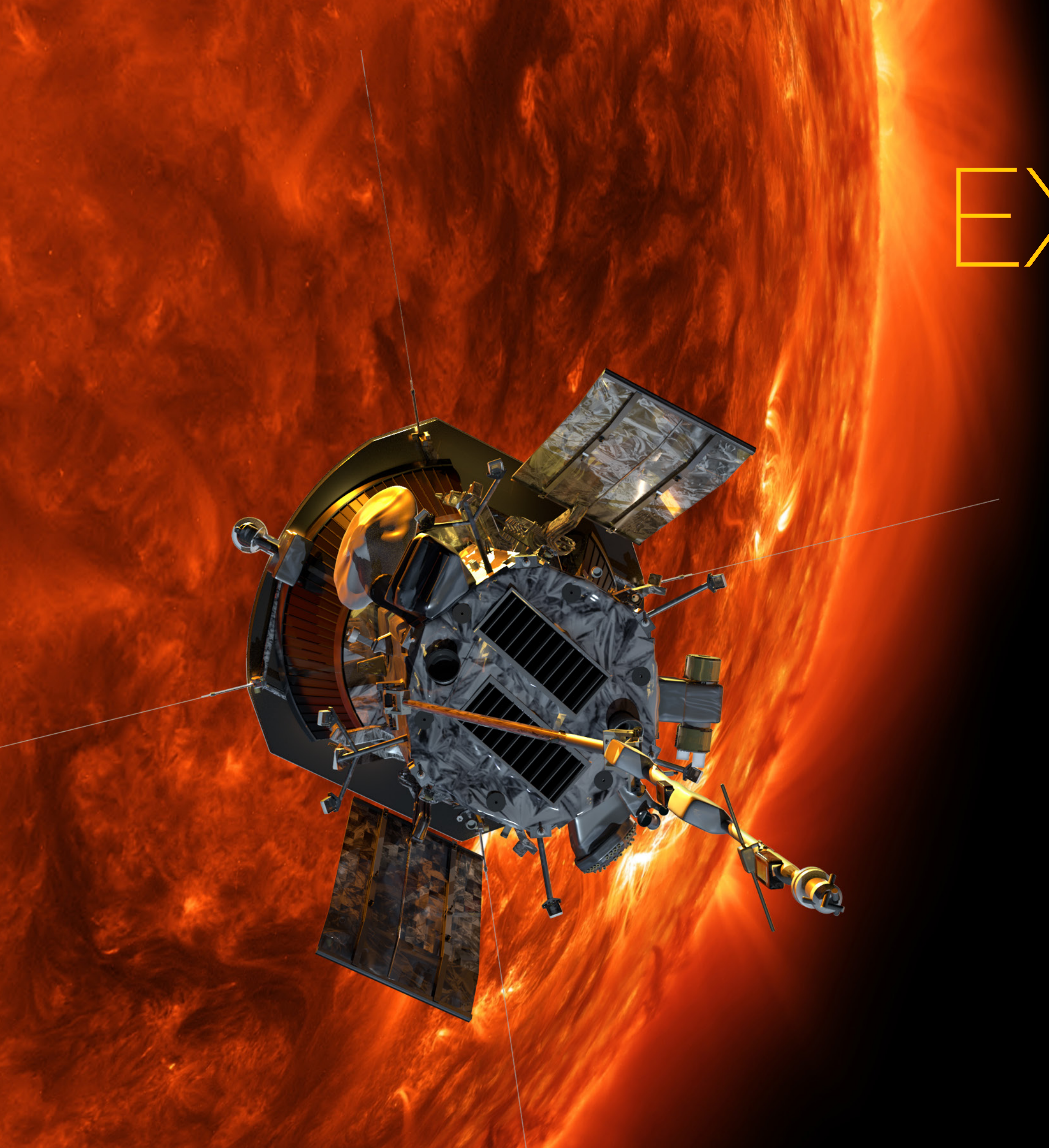
## FROM TODAY TO 2050

While developing autonomous systems for today, the Laboratory is also thinking far into the future. However, in today's world — one characterized by lingering effects of a global pandemic, resource constraints, adversarial threats and ongoing operations — proactively thinking about and planning for technology beyond tomorrow is easier said than done. To aid in this endeavor, APL hosted a workshop in December that looked at the future of autonomous systems and their ability to change concepts of operation into 2050 and beyond. The event was the first of its kind as part of a new Laboratory-led initiative called "Here to There." The initiative aims to spark broader thinking on how to map technologically and operationally relevant paths that can bring far-future visions of defense technology to fruition.

Using 2050 as an orienting benchmark, APL designed the interactive workshop to help participants — including senior naval leaders — picture themselves in a world infused with not-yet-realized technological capabilities. In this imagined setting, APL and workshop participants considered novel operational concepts and identified processes that could shape that future technology adoption. Because the world of 2050 will belong to the next generation, the event purposely included and relied on the perspective of leading midshipmen from the Naval Academy.

The Laboratory's aim is for the defense community to continue to apply this style of collaboration, and the larger spirit and methodology of "here to there" thinking, in exploring other future-enabling technologies across military services.

Whether focusing on the operational challenges of today, tomorrow or further in the future, APL relies on and reaches into its deep history in national defense. As the Laboratory passes knowledge, resources and expertise down to new staff members, and across to new mission areas, it continues to hone its acute understanding of shifting challenges and how to shape technologies that rise to meet them.



# EXPLORING
## EXTREME FRONTIERS

At close to 2 million degrees Fahrenheit, the solar atmosphere, or corona, is a brutal environment for a spacecraft to endure, but with Parker Solar Probe, APL's engineers made it happen. With ingeniously designed water-cooled solar panels and a 4.5-inch-thick heat shield of carbon composite foam, topped with reflective ceramic paint, the probe's onboard electronics sit in a remarkably comfortable 85 degrees Fahrenheit. So as the spacecraft dives into the atmosphere of a blazing star, the interior feels as if it's sitting out on a warm summer day.

On April 28, 2021, after three years in space and seven flybys of the Sun, NASA's Parker Solar Probe officially did what the Laboratory's researchers and engineers had always dared it to do: It entered the Sun's atmosphere – the first spacecraft in history to do so.

Artist's impression of NASA's Parker Solar Probe, a product of APL ingenuity and the first spacecraft to actually "touch the Sun."

FOR THE FIRST TIME IN HISTORY, A SPACECRAFT HAS TOUCHED THE SUN.

What's the view from inside the Sun's corona? Parker Solar Probe's visible-light camera answered that question for the first time with these images of dynamic structures called "streamers." (Credit: NASA/Johns Hopkins APL/Naval Research Laboratory)

> "Flying so close to the Sun, Parker Solar Probe now senses conditions in the corona that we never could before. We can actually see the spacecraft flying through coronal structures that can be observed from Earth during a total solar eclipse."
>
> **— NOUR RAOUAFI, Parker Solar Probe Project Scientist**

From this balmy position, the probe's onboard camera safely captured video of ribbon-like coronal streamers dancing above and below the spacecraft — views only possible from inside the Sun's corona.

"Flying so close to the Sun, Parker Solar Probe now senses conditions in the corona that we never could before," said Nour Raouafi, the Parker Solar Probe project scientist at APL. "We can actually see the spacecraft flying through coronal structures that can be observed from Earth during a total solar eclipse."

At 14.87 solar radii (about 6.47 million miles) from the Sun's surface, Parker Solar Probe passed through a coronal pseudostreamer — a bright loop-like structure that ascends high above from the Sun's surface. The spacecraft suddenly found itself in a region where the chaotic shower of particles from the Sun's solar wind had slowed and the environment quieted, as if entering the eye of a storm.

Parker Solar Probe is one of APL's most innovative and daring engineering and exploration projects, and its scientific returns have been numerous, groundbreaking and often surprising.

In 2019, the spacecraft tracked the origin of magnetic zigzags called switchbacks in the solar wind to the Sun's photosphere, where they emerge from magnetic funnels cribbed between convection cells. In 2021, the probe used its two telescopic cameras to capture the first complete image of Venus' dust ring — a band of particles stretching the entirety of Venus' orbit that scientists had only glimpsed before. And in a complete surprise, the spacecraft's wide-field imager, WISPR, returned a stunning view of Venus during its flyby in July 2020 that ostensibly shows nightglow — the light emitted by oxygen atoms as they recombine into molecules — as well as a look at Aphrodite Terra, the largest known highland region on the surface.

For its contribution to aerospace and its efforts to untangle the web of solar mysteries that have persisted for decades, in the summer of 2021 the Parker Solar Probe team earned the National Space Club and Foundation's Nelson P. Jackson Award, which recognizes those who made the most outstanding contributions to aerospace during the previous year.

"The recognition is another testament to the mission's success and reflects how important it is to not only study the Sun and its immediate environment, but also pursue space exploration in general, as the science community continues pushing the boundaries of space research," Raouafi said. "Parker Solar Probe is exceeding all expectations, and the mission science return has just been amazing."

Parker Solar Probe, however, is just one of several projects APL engineers and scientists are developing to provide cutting-edge science and capabilities for the most extreme places — from the depths of the ocean to the most hazardous environments of the solar system.

NASA's Parker Solar Probe captured stunning views of Venus during its close flyby of the planet in July 2020. (Credit: NASA/Johns Hopkins APL/Naval Research Laboratory/Guillermo Stenborg and Brendan Gallagher)

“These coatings are enabling defensive capabilities that will help the United States maintain the decisive advantage in the hypersonic domain.”

— **JIM SCHUH, Assistant Program Area Manager, Integrated Warfare Systems**

October 2021: With key support from APL and other mission partners, the Navy and Army successfully tested advanced hypersonic technologies, capabilities and prototype systems in a realistic operating environment. (Credit: U.S. Navy photo courtesy of Sandia National Laboratories)

APL’s state-of-the-art thermal spray facility enables applications of a wide range of hypersonics coatings, from liquid solutions to solid particulates, such as refractory ceramics.

## MEETING THE NEEDS FOR SPEED

Inspired by the extreme capabilities of Parker Solar Probe’s heat shield, APL materials scientists are developing new protective coatings for a more Earthbound challenge: protecting hypersonic vehicles.

Because they cruise at more than five times the speed of sound, hypersonic vehicles create an extremely hot and erosive environment around themselves. Each craft’s nose, fins, control surfaces and apertures face temperatures exceeding 1,800 degrees Fahrenheit, oxidation from the surrounding atmosphere and incredible aerodynamic shear forces that can dismantle components.

With the capability to withstand extremely high temperatures, the ceramic coating on Parker Solar Probe’s heat shield offered a promising launch point. APL researchers and engineers had specially developed it so the material could attach to a carbon substrate without chemically reacting and maintain its structural integrity and volume while cruising through hot plasma at more than 400,000 miles per hour.

Tony Ahan adjusts Parker Solar Probe’s Thermal Protection System (TPS) before attaching it to the spacecraft. Able to resist extremely high temperatures, the white ceramic coating on the TPS offered a starting point for researchers looking to protect hypersonic vehicles.

The leading edges of hypersonic vehicles — as well as fins, control surfaces and apertures — need to be protected against speeds exceeding Mach 5, temperatures well above 1,800 degrees Fahrenheit, oxidation from the atmosphere and tremendous aerodynamic shear loads. Custom materials can enable mission success in these extreme environments.



“But we can’t just take Parker Solar Probe’s heat shield coating and apply it to a hypersonic vehicle. Space is an airless environment, but the upper atmosphere is not.”

— **KEITH CARUSO, Mechanical Engineer**

“But we can’t just take Parker Solar Probe’s heat shield coating and apply it to a hypersonic vehicle,” said Keith Caruso, an APL materials expert and mechanical engineer who was a key contributor to Parker’s coating. “Space is an airless environment, but the upper atmosphere is not. Hypersonic vehicles have to deal with a very specific and demanding set of environments that space vehicles don’t face.”

Leveraging decades of research on hypersonic systems, along with specially designed facilities for simulating temperatures experienced at hypersonic speed and for spraying liquid solutions and particulates, such as refractory ceramics, APL has been paving the way for the development of numerous coatings and materials meant for the hypersonic environment.

“These coatings are enabling defensive capabilities that will help the United States maintain the decisive advantage in the hypersonic domain,” said Jim Schuh, who is the assistant manager of APL’s Integrated Warfare Systems Program Area.

Using strategically invested internal funds and external partnerships, APL researchers have rapidly established systems and capabilities enabling coatings developments that meet a variety of demands for offensive and defensive hypersonic missions.

## SOLVING A STICKY-LESS SITUATION

Other APL scientists and engineers, however, were looking not at developing materials for high velocities and extreme temperatures but at something that's seemingly more fundamental: getting glues to stick under water.

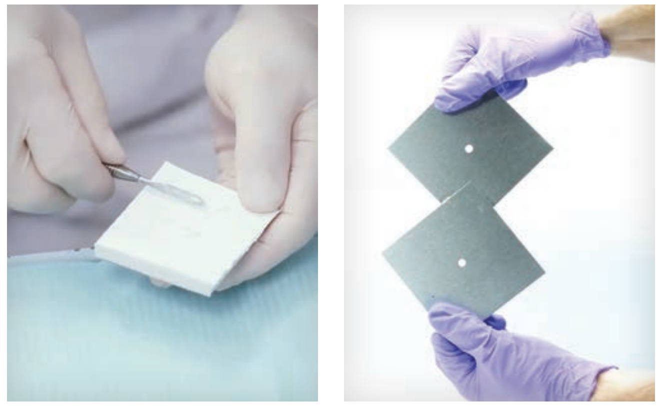
Finding adhesives that can rapidly attach to underwater surfaces and hold strongly — to adhere reinforcing material to the underwater support beams of damaged bridges, for instance — has remained an issue for the Navy and various maritime industries mostly because they're waging a fight against the organisms that they don't want to stick.

"Most surfaces underwater are built to prevent adhesion," said APL chemist Reid Messersmith. "Living organisms spend a lot of energy to prevent things from sticking to them, and human vessels all have coatings to increase smoothness and prevent organisms from fouling the surface."

The challenge is only exacerbated by the slow cure rate of polyurethane resins that glues are made from — which can take at least 24 hours to properly set — and the salt water that reacts to degrade most adhesives. Altogether, underwater adhesives had been mostly ineffective.

Messersmith and his team, however, developed an adhesive "supplement" that could accelerate the curing process and prevent water from infiltrating, which the group detailed in a scientific paper published in the American Chemical Society's Applied Polymer Materials journal in 2021.

"We made it strong and fast, from 24 hours to one minute," Messersmith said. "If you can actually let it sit for 24 hours, it'll hold at 10 times the strength."



APL researchers created an additive that transforms commercial glue into a rapidly curing underwater adhesive that can bond to aluminum, stainless steel, glass and plastic.

Rather than creating an entirely new adhesive, the trick to their incredible time-cut was to add a chemical catalyst and a crosslinker; the catalyst would rapidly activate the glue so it adheres, and the crosslinker would ensure the glue holds strongly to the surface. With the catalyst and crosslinker molecules packaged in microcapsule shells that are added to the original polyurethane glue, a person can simply add the shells to an adhesive, apply it to an object, position the object into place and then rub or press the adhesive so it breaks the shells and releases the catalyst and crosslinker. In about a minute, the glue will cure under water and effectively attach to aluminum, stainless steel, glass or plastic.

While Messersmith said the team is still working on getting adhesives to attach to biofouled surfaces, this first result was a massive and exciting step toward solving this ongoing problem.

"You can imagine in a marine environment how needing 24 hours to cure and adhere at full strength could be an issue. So we made it strong and fast."

— **REID MESSERSMITH, Chemist**



"We've been working on metallic shape-memory materials for a few years, and we were challenged to also consider what could be achieved with soft stimulus-responsive shape-changing materials."

— **MORGAN TREXLER, Program Manager, Science of Extreme and Multifunctional Materials**

## FLEXIBLE ROBOTICS FOR A FLEXIBLE APPROACH

Researchers have increasingly looked into soft robotic technology for its many possible applications in challenging environments. Many see it offering a nimble alternative to risking human or animal lives while performing precarious duties, such as a search and rescue operation amidst the rubble from a natural disaster or defusing an explosive on land or under water.

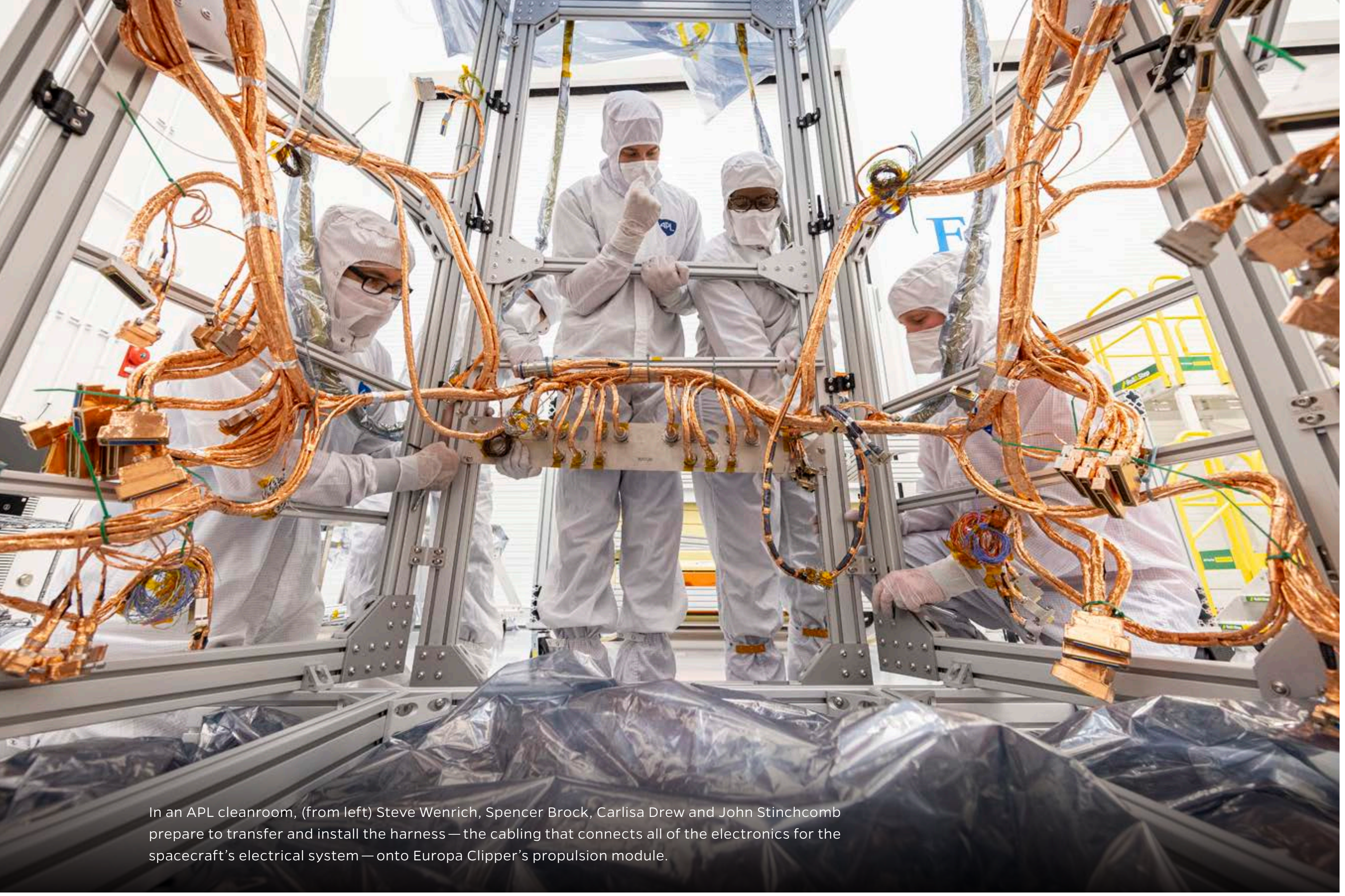
APL's technology uses liquid crystal elastomers that can turn rubber strips or other flexible materials into muscle-like actuators when they are embedded and heated. But a major challenge has been detaching the robot from its metaphorical umbilical cord — a tether to its outside power source.

Without that tether, soft robotics have been limited by lower power capabilities and slower response times. But Zhiyong Xia, a polymeric materials expert at APL, and his team have been developing soft robotics that can remotely activate with the press of a button on a smartphone.

In 2021, Xia and colleagues used a system-level engineering approach to build a snail-like robot with a large elastomer shell that houses the machine's control panel and power source and rubbery pink strips that quickly respond by curling and extending like an inchworm with just the tap of a button on a smartphone — no strings attached.

"We've been working on metallic shape-memory materials for a few years, and we were challenged to also consider what could be achieved with soft stimulus-responsive shape-changing materials," said Morgan Trexler, who manages APL's Science of Extreme and Multifunctional Materials Program. "Analyzing the possibilities from the materials perspective, and also thinking about unique expertise areas at APL, we saw an opportunity to make an impact in soft robotics, where materials advances are critical, but integration with other technology advances, such as in robotic controls is also needed to make an impact."

This snail-like soft robot was born from an APL idea to give liquid-crystal elastomer legs a shot of thermal energy-inducing electrical current — and control the entire process with a smartphone.



In an APL cleanroom, (from left) Steve Wenrich, Spencer Brock, Carlisa Drew and John Stinchcomb prepare to transfer and install the harness — the cabling that connects all of the electronics for the spacecraft's electrical system — onto Europa Clipper's propulsion module.

## FROM OCEAN WORLDS TO THE SOLAR SYSTEM'S EDGE

APL's preparations to explore extreme environments outside our home planet go beyond our star. While Parker Solar Probe came closer to the Sun than any spacecraft before it (and will continue to surpass its own records for three more years), the Lab also probed novel ways to explore our solar system and discover where it may harbor the building blocks of life as we know it, particularly Jupiter's moon Europa.

Beneath its icy surface, Europa likely harbors a liquid water ocean with twice the amount of water found collectively in Earth's oceans. That, in combination with the heat generated by the punishing tidal forces Jupiter imposes on the small moon and geologic faults that may open to the ocean depths below, makes Europa potentially suitable to support living organisms.

But the frigid, atmosphereless moon sits in a bath of powerful radiation, the most intense in the solar system. Reactive ionized particles — some of which Jupiter's magnetic field propels to nearly the speed of light — can easily fry electronics, leaving spacecraft damaged or inoperable.

The design of NASA's Europa Clipper, which APL engineers have been developing jointly with the agency's Jet Propulsion Laboratory and dozens of other universities and laboratories, will not only shield the spacecraft's sensitive instruments from the surrounding hazardous environment but even exploit the radiation to reveal the depth and conductivity of Europa's ocean.

The mission's design includes a thick aluminum vault that will protect the instruments' electronics from the harsh radiation around Jupiter. It also features a towering APL-built propulsion module that contains twin cylinders lined with thermal tubing to carry coolant that will prevent the spacecraft from getting too hot or too cold while in deep space.

Europa Clipper's sophisticated design passed a critical NASA review in April, a major milestone in the spacecraft's development. Since then, mission teams across the United States and Europe have been constructing Europa Clipper's complex pieces, including its nine science instruments. APL leads the development of the Europa Imaging System (EIS),



"With Europa Clipper, we're developing technology to help answer a fundamental space science question: Could life exist on other worlds?"

— **CARLISA DREW, Europa Clipper Propulsion Module Harness Lead Technician**

which will capture high-resolution images and map about 90% of the moon's surface at 330 feet per pixel, and the Plasma Instrument for Magnetic Sounding (PIMS), which will study the density, temperature and flow of plasma (charged particles) near Europa as Jupiter's magnetic field washes over the moon. Using this plasma and the magnetic field that Jupiter induces around Europa, PIMS will precisely determine Europa's ice shell thickness as well as its ocean's depth and conductivity.

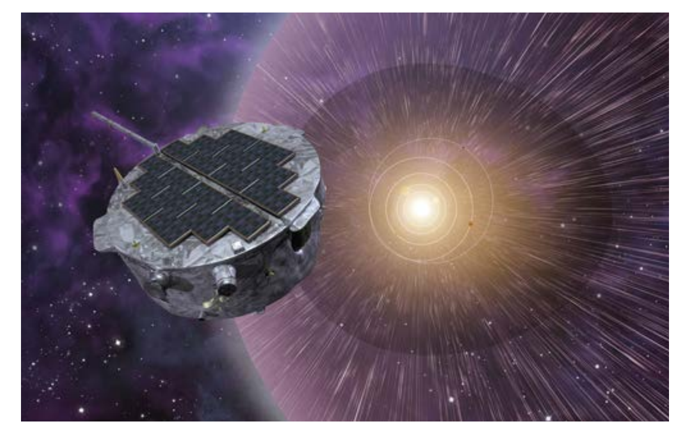
APL's focus on extreme plasma environments doesn't stop at Jupiter, however. NASA's Interstellar Mapping and Acceleration Probe (IMAP) mission, which APL will design, build and manage with Princeton University at the helm, extends that interest to the very edge of the solar system.

As the fifth mission in NASA's Solar Terrestrial Probes program, IMAP will deepen our understanding of the boundary of the heliosphere, the protective bubble surrounding the solar system created by the Sun's solar wind and magnetic field. From a special gravitationally balanced point between Earth and the Sun, IMAP will investigate how the Sun accelerates the particles that form the heliosphere to over 1 million miles per hour. It will probe how the particles interact with the interstellar medium and help researchers better understand how the heliosphere filters the Milky Way galaxy's high-energy particles from entering the solar system.

After years of design and conceptualization, IMAP team members defended their mission and spacecraft design in May 2021 — including science objectives, requirements, cost and schedule — during a preliminary review with NASA. They passed, marking a significant milestone that underscores the team's dedication to meeting the logistical and technical requirements of such a challenging and ambitious mission.

Ultimately, that is the forte of APL scientists and engineers — to be bold and carry out ambitious ideas. Despite the risks and challenges of exploring some of the most extreme environments on Earth and worlds beyond, APL scientists and engineers continue to make daring leaps and press ahead with ingenuity and creativity.

Artist's impression of the Europa Clipper. Coming together in a partnership between APL and the Jet Propulsion Laboratory, the spacecraft will investigate the habitability of Jupiter's large icy moon, Europa. (Credit: NASA)



Artist's impression of the Interstellar Mapping and Acceleration Probe (IMAP). The mission will help us better understand the flow of particles from the Sun, called the solar wind, and how those particles interact with space within the solar system and beyond. (Credit: NASA/Johns Hopkins APL/Princeton University/Steve Gribben)

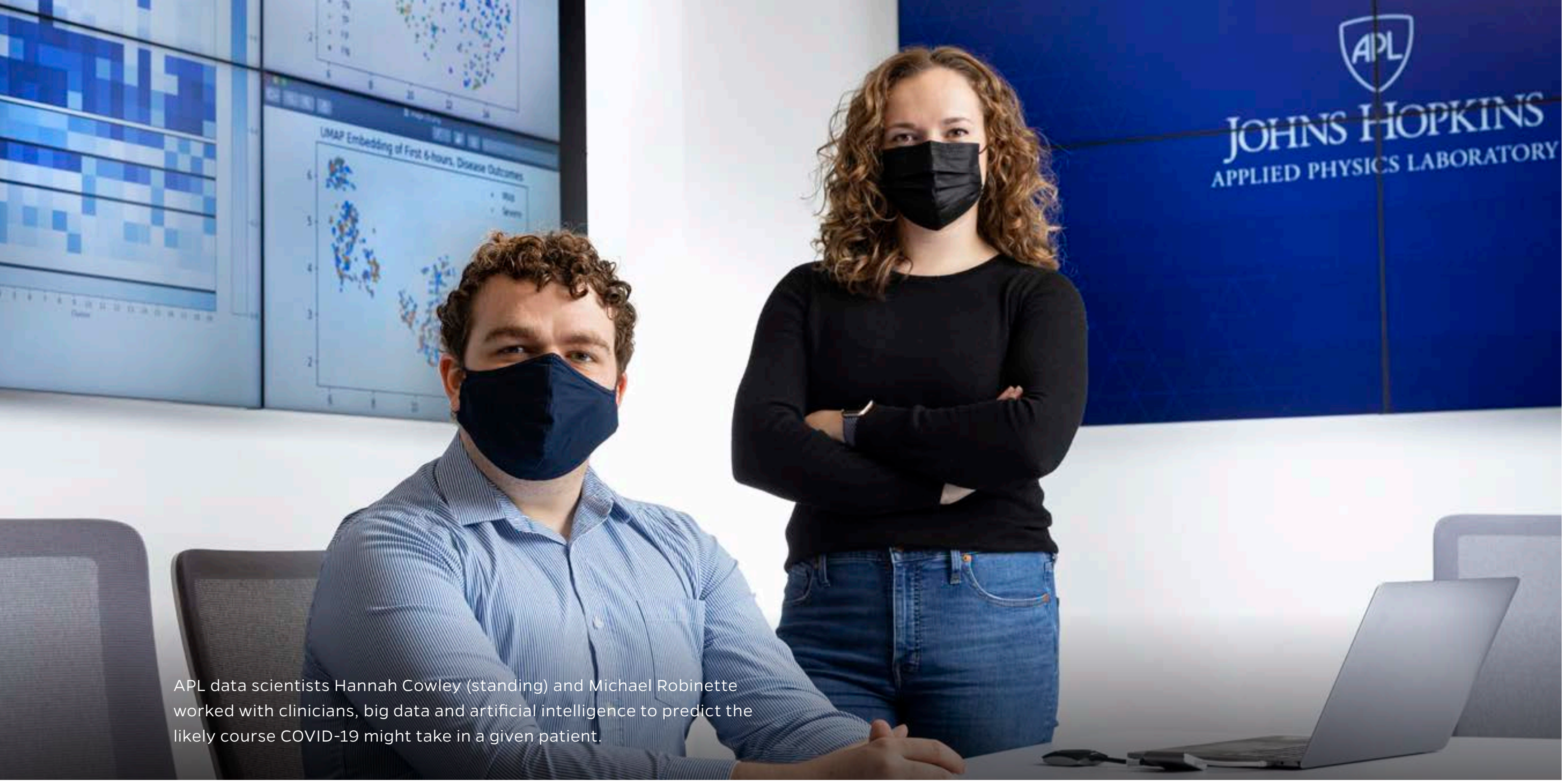
COUNTERING EVOLVING THREATS TO NATIONAL

# SECURITY

When APL was founded, its charge was to provide technological breakthroughs for a nation at war. While America's critical challenges and threats have evolved, expanded and multiplied in the last eight decades, the Laboratory's focus on protecting national security, no matter the domain, has remained steadfast.

The Laboratory continues to anticipate and proactively respond to many of the nation's evolving – and sometimes unconventional – security challenges, from health security to cyber, U.S. infrastructure and the environment.

Beatrice Garcia monitors the Johns Hopkins COVID-19 Dashboard in APL's Live data, Integration, Validation and Experimentation (LIVE) Lab, a nerve center featuring cutting-edge tools that help cyber operators detect, understand and respond to cyberattacks across many platforms and applications.




APL data scientists Hannah Cowley (standing) and Michael Robinette worked with clinicians, big data and artificial intelligence to predict the likely course COVID-19 might take in a given patient.

## THE SUBSET SEEKERS

Johns Hopkins Medicine's biocontainment unit in downtown Baltimore, one of 10 federally funded infectious disease treatment centers across the nation, was among the first to activate when COVID-19 broke out in the U.S. It had been preparing for viral outbreaks since 2014, so in March 2020, the nation turned to the unit to help anchor the U.S. response to the novel coronavirus.

Within a few weeks, though, there were more patients than the unit could handle. The connections between patient, symptom and disease trajectory — whether a person would become a mild or severe COVID-19 case — became increasingly unclear.

A fit, active man in his 30s struggled on a ventilator for 40 days. Meanwhile, in France, a 117-year-old nun contracted the disease, fully recovered and didn't even know she had it. To explain this shocking difference, Dr. Brian Garibaldi, who directs the Johns Hopkins biocontainment unit, and a small team of APL data scientists — Will Gray Roncal, Hannah Cowley and Michael Robinette — leveraged their skills in big data and machine learning to better predict patients' probable disease courses and identify unique treatment needs. The team aimed to identify patient subtypes and calculate which disease course was most probable for each.

APL sorted data collected from 1,182 COVID-19 patients from March to August 2020. The team created an algorithm to predict a patient's most likely course two weeks from the time they were admitted to the hospital. Then they instructed a computer to cluster the same data on its own and find patterns that would be extremely difficult, if not impossible, for a human to identify — a process called unsupervised machine learning. Combining the methods, the team found patients fell into 20 clusters, divvied up by specific symptoms — muscle pain, chills, vomiting, loss of taste and smell, sore throat and fatigue — and comorbidities that included cardiovascular disease, hypertension and diabetes.

> "The pandemic has shown how important data analysis is in so many different facets of health."
>
> — **WILL GRAY RONCAL, Electrical Engineer and Data Scientist**

In two clusters, for example, 90–92% of people followed a mild disease course, and oddly, those people tended to have fewer comorbidities but more severe symptoms. However, of greatest interest (and most concern) were five clusters in which more than 5% of patients, a standard threshold of statistical significance, were predicted to follow a mild disease course but ended up becoming severe cases.

Garibaldi found these anomalies fascinating. "We can learn from those patients," he said. "And hopefully, as we develop better ways of treating the complications of COVID and being able to better impact the disease trajectory, it can help us identify the right patients for the right treatment at the right time."

That is where the true promise of these techniques lies. The APL team is studying how they would implement the prediction power of this machine learning algorithm in hospitals for other emergent diseases requiring rapid response, enabling clinicians to directly make on-the-spot decisions.

Creating and launching a medical tool requires tests, certifications and federal approvals, though. To do so, they know they'll need to shepherd the model through rounds of peer review and continually improve it. They are also further understanding differences between clusters and are considering collaborating with other institutions to access more datasets, all in an effort to take this precision medicine initiative further than any before — because these lessons will be valuable long after the pandemic has hopefully subsided.

"Clinicians are going to be researching this event for years to come," Cowley said.

"The pandemic has shown how important data analysis is in so many different facets of health," Gray Roncal said. "We think this could be a seminal moment in leveraging precision medicine to empower clinician scientists and patients to determine individualized approaches to diagnosis, prognosis and better care."

## ENABLING GLOBAL GENOMICS WORK

While one team continues to trace the impacts of COVID-19, the disease, other researchers at the Laboratory worked in 2021 to continue tracking the virus that causes it, SARS-CoV-2, and the mutations that have prolonged the pandemic worldwide.

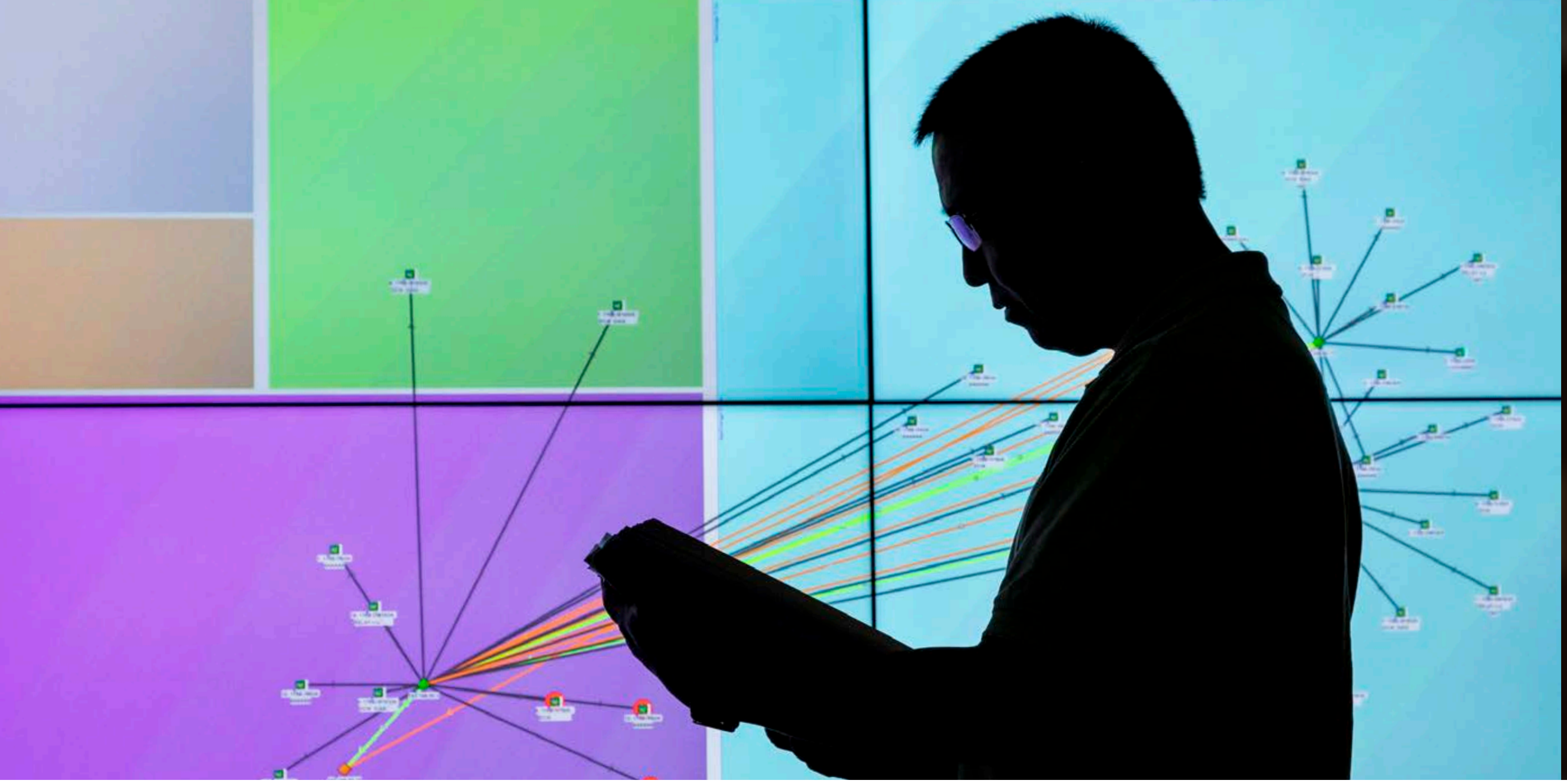
With support from the National Institutes of Health Fogarty International Center and the Association of Public Health Laboratories, APL researchers developed a modular, open-source software suite that makes advanced genomics tools accessible and user-friendly for scientists and public health workers around the world. The tool, called Basestack, made an immediate impact on the global genomic surveillance efforts during the COVID-19 pandemic.

As the pandemic continues to rage, tracking virus variants is increasingly important in understanding virus evolution, transmission and spread to advise pandemic response. However, genomics work has historically been the province of highly specialized laboratories with access to top-of-the-line hardware, infrastructure support, high-speed internet and technical expertise.

With Basestack, those applications can now be run locally, on off-the-shelf laptops, by way of a clean and intuitive interface. Its ease of use is demonstrated by the fact that Basestack is now enabling genomic infectious disease surveillance in more than 20 countries.

By reducing the technical lift required to establish local sequencing capacity, Basestack and virtual conferencing platforms made it possible for end users to be trained remotely and quickly, getting them fully up to speed in their own labs. This ultimately enabled labs to effectively and efficiently conduct reproducible sample analysis in an independent manner. Compared to current standard practice, this decentralized approach has and will continue to enable broader global knowledge of SARS-CoV-2 sequence diversity.

In early March, APL molecular biologist Peter Thielen worked to sequence SARS-CoV-2, the virus that causes COVID-19, at Johns Hopkins Hospital.



"The growing applications for autonomous systems in the ocean environment make this a tremendously rich and rewarding area to work in. It has a lot of tough and important problems that have big impacts on society as a whole."

— **JAMES BELLINGHAM, Executive Director, Johns Hopkins Institute for Assured Autonomy**

## COMBATING MISINFORMATION AND CYBER THREATS

As COVID-19 vaccines became increasingly available in the U.S. in 2021, one of the biggest challenges facing public health practitioners was countering misinformation. That was not a challenge exclusive to the pandemic. Defeating coercive information campaigns online, protecting the nation's infrastructure against cyberattacks and working toward greater assurance in our increasingly autonomous world were all Laboratory priorities in 2021.

Cyber targeting of public infrastructure, such as the well-reported attack on a municipal water plant in Oldsmar, Florida, in February 2021, is a familiar threat. Cybersecurity researchers at APL—recognizing the vulnerability of public infrastructure—stood up the Critical Infrastructure Protection Group six years ago to study these concerns and address possible solutions. The Laboratory is designing cost-effective cyber defense technologies that are strong enough to repel serious attacks but affordable enough to be easily implemented, for example, by the nation's diverse water treatment plant operators—including many municipal operations with constrained budgets and small IT departments.

The water treatment testbed in the CYber Physical REsilient Systems Solutions (CYPRESS) laboratory at APL was used for an operational pilot at a municipal water treatment facility in Maryland, using APL research technologies to demonstrate a Resilient Industrial Control System (ICS).

The technologies included capabilities to detect whether an adversary has changed the system's values, even when the expected values continue to be displayed to the operator; to divert an intruder to a high-quality decoy, protecting critical equipment while gathering intelligence about that intruder; and to transfer control of critical processes and maintain continuity of operations if the ICS is attacked.

The results of the pilot, and other demonstrations of the Resilient ICS, found that the APL technologies could successfully prevent, detect and mitigate cyberattacks on an


From left, Ryan Silva, Joe Maurio and Alex Beall employ the water treatment testbed in APL's CYber Physical REsilient Systems Solutions (CYPRESS) laboratory for a look at technologies that would improve the resilience of the nation's industrial control systems.



ICS. APL continues to closely collaborate with government sponsors on further safeguards and sharing its technologies and approach with the wider community.

But targeted attacks themselves are only part of the cyber threat.

In APL Senior Fellow Paul Stockton's paper, Defeating Coercive Information Operations in Future Crises, he explains how the rise of social media and sophisticated technologies can help the nation's adversaries spread falsehoods that can shape their victims' perceptions and coerce them to yield in future crises.

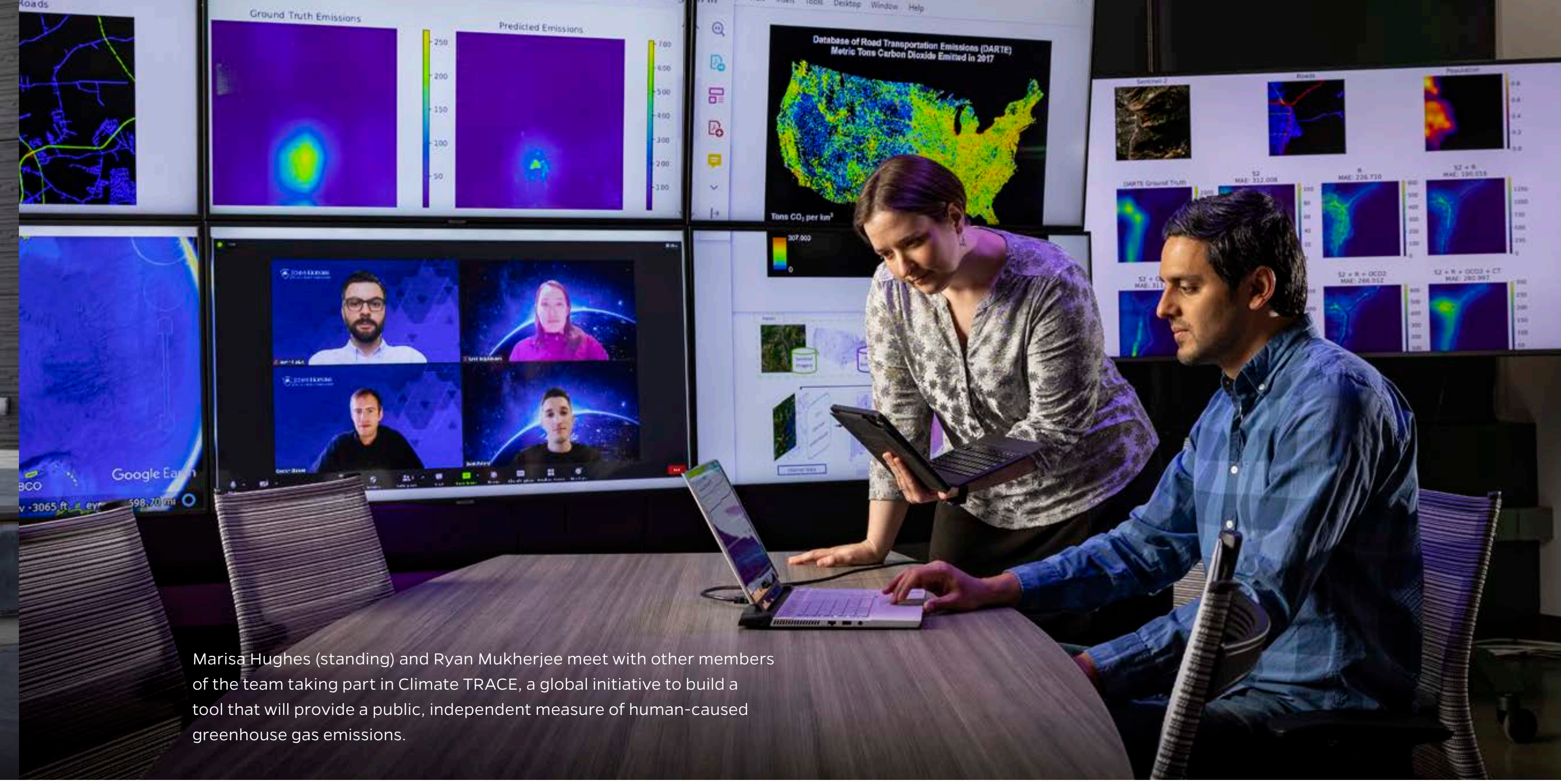
The threats of ICS attacks and coercive information operations create evolving hazards that adversaries could deploy in a myriad of ways, making assurance of our increasingly autonomous technology all the more paramount.

In 2021, as APL advanced several projects aimed at building trust in artificial intelligence (AI) and autonomous systems, it also welcomed James Bellingham—a pioneer in the worldwide autonomous marine robotics field—with joint appointments as the executive director of the Johns Hopkins Institute for Assured Autonomy (IAA), Johns Hopkins Bloomberg Distinguished Professor and a senior advisor in APL's Asymmetric Operations Sector. For more than 30 years, Bellingham has been a global leader in the development of small, high-performance autonomous underwater vehicles, resulting in a class of systems that are now widely used within the military, industry and science communities. He joined Johns Hopkins from the Woods Hole Oceanographic Institution, where he was founding director of the Consortium for Marine Robotics.

In 2020, Johns Hopkins University committed $30 million to establish the IAA as a national center of excellence for assured AI and smart autonomous systems, run jointly by APL and the Whiting School of Engineering as partners. As smart, connected devices, cars, homes, offices and cities proliferate with increasing autonomy, national leaders are taking action to assure the safety of the technology, build public trust and defend against cyberattacks. IAA's mission is to advance research that will assure the development of smart, autonomous machines and systems and to ensure their integration in society is beneficial, safe, secure, reliable and ethical.

From improving autonomous vehicle safety and traffic management to increasing the resilience of deep learning systems in domains such as transportation and medicine, the IAA's research continued apace in 2021.

From left, APL's Zhiyong Xia, James Johnson, Jesse Ko, Leslie Hamilton, Dajie Zhang, Danielle Schlesinger and Nam Le devised a method to eliminate PFAS — so-called "forever chemicals" — from water.



Marisa Hughes (standing) and Ryan Mukherjee meet with other members of the team taking part in Climate TRACE, a global initiative to build a tool that will provide a public, independent measure of human-caused greenhouse gas emissions.

> "Our team is working to do the extraordinary: develop novel catalyst technologies to break the toughest bonds in hazardous materials."
>
> — **ZHIYONG XIA, Chief Scientist and Project Manager**

## EVALUATING SECURITY IN A CHANGING CLIMATE

This year, APL also focused on how AI, machine learning and many other tools previously applied elsewhere could be utilized by researchers to understand how climate challenges will impact national security. The Laboratory drew together diverse expertise to search for ways to have the biggest impact and invested in a series of efforts.

As part of a suite of water-related efforts at APL, scientists devised a unique, inexpensive and scalable method for destroying a group of ubiquitous and toxic environmental chemicals — forever. The technique uses a novel, cost-effective catalyst to induce an electrochemical reaction that breaks the powerful carbon-fluorine (C-F) bonds that hold these toxic chemicals together.

PFAS, or perfluoroalkyl and polyfluoroalkyl substances, are a group of artificial chemicals commonly found in cookware, carpets, outdoor gear, food packaging, aqueous film-forming foams for firefighting and a plethora of other industrial applications. They're also commonly found in water and consequently ingested by wildlife and humans. Their tendency to linger indefinitely in the environment without degrading has earned PFAS the label "forever chemicals." Most methods developed to deal with PFAS in water have focused on PFAS sequestration via filters or similar technologies. However, while filtration is helpful it does not eliminate the harmful chemicals from the environment, which is truly what's needed.

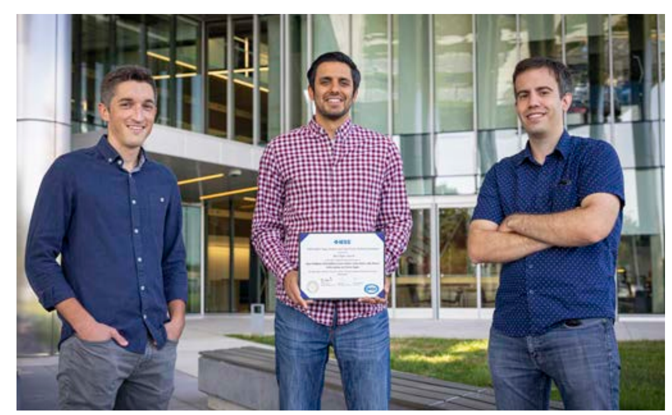
Using an APL-developed electrochemical catalyst — made from titanium oxide intentionally mixed with niobium — the Lab's scientists were able to break the notoriously tough C-F bonds found in PFAS and turn them into environmentally benign species. Further, in an effort to avoid using precious materials in their process (which can make any solution too costly to employ at scale), the team guided its catalyst design with atomic-level simulations. After narrowing the candidates, the researchers created and tested promising catalysts for laboratory evaluations. This method, the team found, can also be used to identify other novel materials and catalysts for a wide range of applications, such as harvesting hydrogen and oxygen from seawater to generate energy or potentially create breathable oxygen.



## CLIMATE TRACE

Another group demonstrated for the first time that road-transport emissions can be accurately estimated in real time from satellite imagery, contributing to a larger effort to monitor greenhouse gas emissions on a global scale.

Climate TRACE, from Tracking Real-time Atmospheric Carbon Emissions, is an initiative to build a tool that will provide a public, independent measure of human-caused greenhouse gas emissions using AI, satellite image processing, machine learning and other remote sensing technologies. It will rely primarily on existing infrastructure — satellites, but also mobility data, drones and land- and sea-based sensors. The tool counts former Vice President Al Gore among its chief funders and supporters, and it was honored as one of the top 100 inventions of 2020 by Time magazine.



From left, Derek Rollend, Ryan Mukherjee and Gordon Christie hold the award for Best Paper in the EarthVision Workshop track from the 2021 IEEE Conference on Computer Vision and Pattern Recognition, earned for APL's first publication related to Climate TRACE.

In conjunction with other data sources, including road network data, population data and satellite- and ground-based data on carbon dioxide concentrations, the APL team was able to use satellite imagery to train and validate machine learning models that can be used to make accurate predictions where direct measurements are not available. Data from APL's models are incorporated into the first public Climate TRACE inventory and dashboard, and the team's initial proof-of-concept results were presented at the 2021 Institute of Electrical and Electronics Engineers (IEEE) Conference on Computer Vision and Pattern Recognition and published in the conference's proceedings, earning the award for Best Paper in the EarthVision Workshop track.

The team is validating its models and iterating them into products that can be used by Climate TRACE, continuing to improve global emissions estimates and incorporating population and infrastructure data to reduce errors.

The Climate TRACE work grew out of a larger APL effort to apply expertise in sensing and modeling to predict Earth system changes, providing data to support decisions on the national security aspects of mitigating effects of climate change.

## PLANET SENSING

APL researchers have also been working on additional remote sensing applications for climate change challenges.

One such example focuses on how ionospheric interference on Earth introduces noise and distorts the desired signals of radio waves, which are modified by the material properties they encounter as they pass through the Earth. To combat that, scientists are developing a model to characterize ionospheric effects on radio frequency (RF) signals to improve sensing of wet and frozen soils. Once implemented, the technology has implications for identifying soil moisture changes due to climate change, as well as for identifying stable areas for launching rescue missions in disaster recovery operations.

Researchers had the idea that if RF energy is sent in at different angles, the emerging energy will spread across a range of angles as a function of subsurface material properties. If different polarizations at the same frequency are passed through the subsurface, the polarizations change as well. As such, for the past three years, Laboratory scientists have been developing reflectometers to track soil moisture that are designed to ride along on communications network satellites in space.

One area for possible application is the Arctic. Recovery operations there are exceedingly difficult, and it's also one of the regions most dramatically impacted by changes in the Earth's climate. In the Arctic Ocean, sea ice extent—the area of ocean with at least 15% sea ice concentration—typically reaches its maximum in March and its minimum in September. However, in recent years, Arctic sea ice extent has steadily decreased in all months, and the 5% of sea ice that lasts year-round is thinner and more fragile.

With sea ice retreat opening large areas of the Arctic, government and commercial maritime activity has increased, meaning weekly and monthly forecasts are needed so ships can proceed safely. Ships in transit in the Arctic basin need to know several days to a week in advance where ice will be and in what state to chart courses and plan for supplies and harborage. But the short-term sea ice forecasts used by civilian and military fleets for navigation in the opening Arctic are currently ad hoc, inconsistent and generally dependent on continuity from current conditions and forecaster intuition, much as conventional weather forecasts were 30 or 40 years ago.

A multidisciplinary Laboratory team is developing advanced models of Arctic conditions and Arctic access at high spatial and temporal resolutions to dramatically improve short-term sea ice forecasting. These models will use unique APL detection methods as well as deep learning methods to provide accurate and timely results by fusing data across multimodal satellite imagery and weather information.

"We need continuous, ubiquitous sensing to understand current states and predict future changes of Earth's systems," said Bobby Armiger, who, along with colleague Marisa Hughes, leads a program to explore the impact of climate change on our world and national security. "The work we are doing in sensing and modeling will provide next-generation data critical to mitigating climate change and its effects."

The challenge issued to the Laboratory in its earliest days, with the nation engaged in World War II, was clear. While threats to the country's security have changed over the last 79 years, APL's ability to innovate and evolve alongside those changes has enabled us to continue tackling those challenges and anticipating future needs, whether for the good of the nation or the planet.

APL experts are developing advanced models of Arctic conditions (at left) at high spatial and temporal resolutions to dramatically improve short-term sea ice forecasting. APL researchers are also examining ways to characterize ionospheric effects on radio frequency signals, potentially improving remote sensing of wet and frozen soils from space.

# BUILDING INFRASTRUCTURE FOR THE FUTURE

In the late 1950s, APL physicists William Guier and George Weiffenbach had an idea that became a Department of Defense program known as Transit—the world's first operational satellite navigation system. Guier and Weiffenbach described the Lab at the time as "an environment that encouraged people to think broadly and generally about task problems, and one in which inquisitive kids felt free to follow their curiosity."

Underlying APL's bold, next-generation solutions are world-class laboratories, research facilities and collaboration spaces that provide an environment ideally suited for the technical experimentation and teamwork required for breakthrough developments.

New facilities across the APL campus, such as Building 201, are designed to foster discovery and encourage trailblazing collaborations that embrace the breadth and depth of APL.

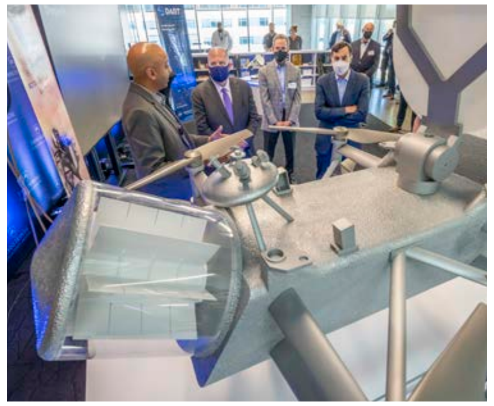
> "These new facilities will provide significant capabilities that enhance APL's ability to make strategically important contributions to sponsor challenges."
>
> **— RALPH SEMMEL, Director**

As APL grew, the environment needed to evolve to match the Laboratory's growth. In the early 2010s, Director Ralph Semmel realized that global events and advances by nation-state near-peers required APL to "up its game" and reignite itself as the "hotbed of innovation." Achieving this would require a well-executed vision and strategy that included multidisciplinary approaches and rapid evolution of technical and research facilities for emerging technologies.

In 2021, APL demonstrated its commitment to that vision by opening three new facilities. Collectively comprising almost 500,000 square feet of research, experimentation and work space, the buildings position APL to remain at the forefront of science and technology exploration, elevating and expanding the Lab's capabilities to anticipate and solve its sponsors' toughest technical problems.

"These new facilities will provide significant capabilities that enhance APL's ability to make strategically important contributions to sponsor challenges," said Semmel at the Building 201 grand opening held in October. "The Lab's continuing investment in our infrastructure will enable us to remain at the leading edge of research and development."

> "APL's campus makes great innovations possible, but the true engine that fuels the unwavering dedication and innovation embodied here at APL is everyone's common belief in serving the public good. The Applied Physics Lab is a national treasure."
>
> **— HEATHER MURREN, Chair, APL Board of Managers**



Maryland Gov. Larry Hogan toured APL's Building 201 upon its official opening. At left, Hogan examines a small chip capable of performing genomic sequencing as APL Board of Managers Chair Heather Murren and Director Ralph Semmel look on; at right, Civil Space Mission Area Executive Jason Kalirai (left) describes the half-scale model of Dragonfly during a presentation on APL-led space missions and initiatives.

## LOWERING BARRIERS AND EMPOWERING PEOPLE

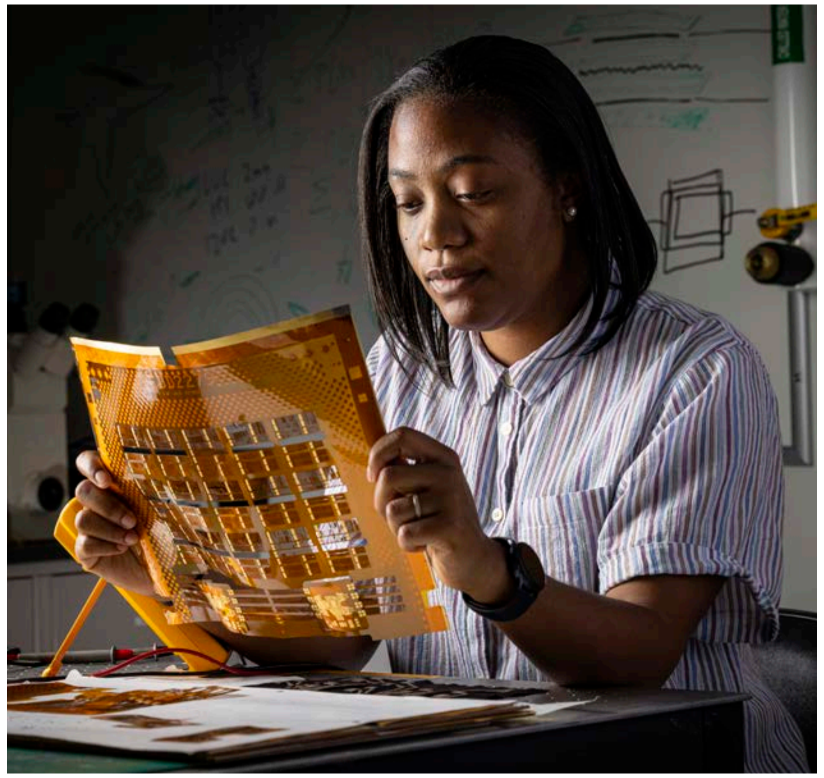
These new facilities stemmed from an assessment of strategic needs, careful planning and best practices learned from previous development across APL's 453-acre Maryland campus. Two spaces, in particular, inspired the layout of Building 201: Central Spark and the Intelligent Systems Center (ISC).

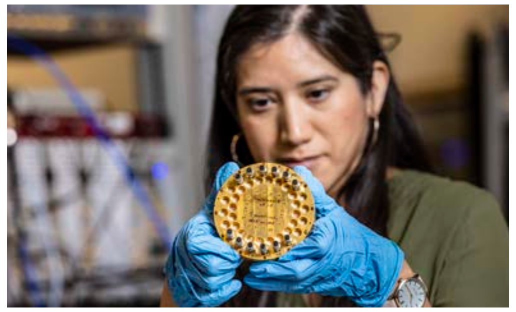
Central Spark, opened in 2014 and dedicated to enabling and supporting staff member innovation, gave APL leadership firsthand experience with an open collaboration space at a relatively low cost. Central Spark's success was such that, in 2020, the Lab nearly tripled its footprint with a move to a fully renovated 9,000-square-foot space. Similarly, the ISC was designed to encourage researchers in robotics, neuroscience, autonomy and information systems to cross paths and collaborate on projects and ideas in the seams between the disciplines.

Increasing the scope of APL's recent open-concept collaboration and work spaces, Building 201 boasts 263,000 square feet of complex, reconfigurable labs and flexible office space housed around a core four-story atrium. The building also contains 90,000 square feet of lab space dedicated to microelectronics, imaging, additive manufacturing, chemistry, biology, quantum computing and other disciplines. With a capacity of 650 staff members, the new building also includes a combination of 100 huddle, conference and breakout rooms, a new STEM Center and 200-person auditorium — and, in 2022, the next iteration of the ISC. Additional capabilities include a molecular beam epitaxy machine, an ultra-high vacuum system capable of achieving incredibly low impurities for creating next-generation nanotechnologies; a gas-phase reactive additive manufacturing tool, designed and built at APL to revolutionize the fields of additive manufacturing and semiconductor synthesis; and a dilution refrigerator for controlling and measuring qubits for quantum computing and capable of reaching temperatures near absolute zero, colder than –450 degrees Fahrenheit.

Housing robust research spaces and capabilities within a secure, open-space environment, Building 201 encourages staff members to embrace a culture of experimentation and connection. In addition to conducting work in one of the building's myriad research facilities, staff members can gather in glass-walled laboratories, conference rooms and huddle spaces or the public auditorium, or outside on the third-floor patio. Building 201 provides staff members with ample resources to strengthen internal relationships, generate new external collaborations and stay easily connected through technological applications.

Building 201 gives APL the unique opportunity to accelerate innovation and realize technology breakthroughs that will help to solve mission-critical problems in national security, space and health.





Clockwise from left, APL researchers Korine Ohiri, Jeffrey Shipp and Mayra Amezcua tap the capabilities of the new quantum computing, biology and microelectronics labs in Building 201.

## SECURING SPACE FOR INNOVATION

In June, APL officially opened the doors to another new facility, Building 14, which is located on the main campus. This building provides the Laboratory's researchers and scientists with additional multidisciplinary space to both undertake fundamental research on operation systems and rapidly respond to and explore new technologies and concepts for national security.

More than 230 staff members occupy the 222,766-square-foot building. This new facility is positioned to enable the development of bold defense solutions and expand the Lab's capabilities in systems integration, reverse engineering, nuclear physics, cyber defense, and communications and radar networks.

"Building 14 offers a wide variety of classified and unclassified laboratories and facilities, enabling numerous collaboration opportunities," said APL's Chief Financial Officer Nick Langhauser. "The work here will necessarily draw upon people from across the Lab, and the value of interdisciplinary collaboration that this building will support is central to the Lab's ability to innovate."

With advanced technical facilities that include flexible high-bay configurations to foster rapid prototyping, cleanroom spaces and a mix of high-tech labs for reverse engineering and cyber tool development, Building 14 is designed to support all types of collaboration and research at both the classified and unclassified levels.

The large expansion of the Laboratory's classified working and laboratory facilities was both a challenge and a great opportunity for all who work on APL's approximately 1,400 classified projects. "Security is a strategic advantage at APL," said APL's Chief Security Officer Leonard Moss. "With the opening of the three new buildings, the Lab has an additional 43,000 square feet of secure space."

"With the opening of the three new buildings, the Lab has an additional 43,000 square feet of secure space."

— LEONARD MOSS, Head, Security Services Department and Chief Security Officer

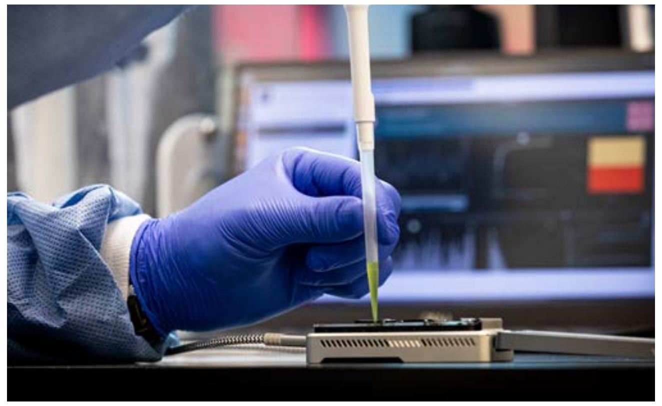
New facilities, such as Building 14 (foreground), elevate APL's ability to meet evolving sponsor challenges, providing staff members with advanced technical resources and capabilities that promote innovation and collaboration.

## ANTICIPATING BIOSECURITY THREATS

Long before the COVID-19 pandemic, APL was equipped to research and quickly respond to biothreats. But in May 2021, less than two years after breaking ground, the new Biosafety Level 3 (BSL-3) facility opened to provide staff members with 4,500 square feet of space for leading-edge biosafety and biosecurity research.

APL is one of only two university affiliated research centers with a certified BSL-3 laboratory. The important work conducted here contributes to a number of programs in homeland protection, health, defense advanced research and special operations. It will also bolster the research done in the Lab's other biosafety laboratories, increasing the nation's capacity for study in this field by 25%.

Access to the facility is restricted and controlled at all times to enable work under Centers for Disease Control and Prevention safety requirements. Diligent adherence to such requirements empowers the APL scientists and researchers to confidently and safely aid the quest for game-changing advances in bioaerosol analysis, DNA sequencing and other domains essential to detecting and characterizing known and evolving pathogens.

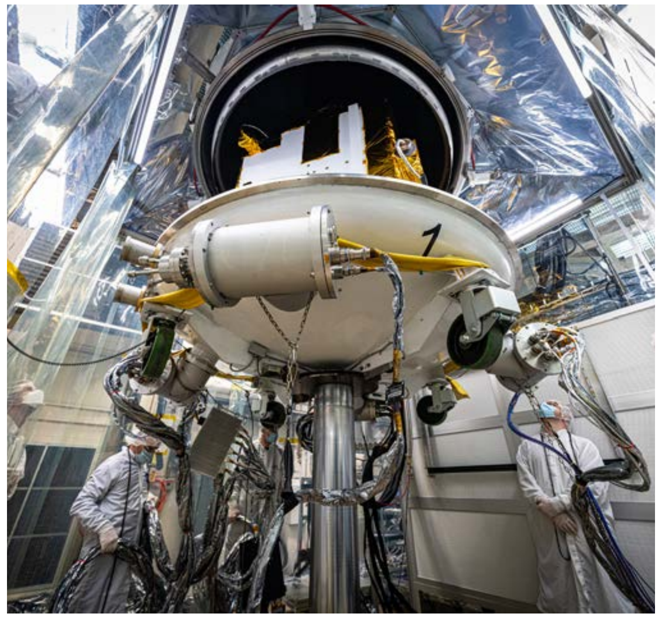


This new facility significantly expands APL's capabilities in leading-edge biosafety and biosecurity research.

## REMAINING AGILE FOR THE FUTURE

In addition to the new buildings, APL has also developed or overhauled new laboratories within existing structures, such as the 800-square-foot temperature altitude chamber created to support NASA's Dragonfly mission to Saturn's moon Titan. The chamber is the only one in the U.S. capable of reaching –180 degrees Celsius at simulated altitudes.

To guide its future investments, APL unveiled a new master plan in March 2021 that focuses on long-term campus development opportunities. Previous iterations of the campus master plan looked ahead seven years and focused on one building at a time; the new master plan provides a framework for developing the campus during the next 20–40 years. It's an outline to address as-yet-unknown sponsor and program needs, evolving aspects of technology, environmental and regulatory requirements, and workplace culture and effectiveness. It will frame short- and long-term development discussions and provide the guidance to continue the Laboratory's efforts in physically creating an environment that says, "this is APL."



APL engineers move the Double Asteroid Redirection Test (DART) spacecraft into a thermal vacuum chamber, where it was subjected to the extreme temperatures and other conditions it will face in space.

# LABS OF THE LAB

## THE WOODS (WORKSPACE FOR INNOVATIVE OPERATIONAL DECISION SYSTEMS AND DATA SCIENCE)

The WOODS is a collaborative space designed to support experimentation and development related to operation centers and decision systems, e.g., for emergency or incident response operations. WOODS resources include high-fidelity displays, collaboration tools and meeting areas. Its reconfigurable design supports 24/7 operations, and it has redundant power and infrastructure to provide resilience. Since May 2020, this space has been the home of the Current Operations team supporting the National COVID-19 Response, providing direct analytic support to the White House, the Centers for Disease Control and Prevention, and the Department of Health and Human Services.

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.

## FACILITY FOR ELECTROMAGNETIC AND RF DIRECTED ENERGY (FEAR-DE)

High-power radio frequency (HPRF) weapon systems use very high-power pulses of electromagnetic energy to disrupt or damage electrical systems, and our adversaries are fielding HPRF weapons that are quickly becoming a threat to U.S. military assets. FEAR-DE offers three large test chambers to support HPRF projects and is equipped with a full suite of RF test equipment, including high-power amplifiers, electric field and magnetic field probes, signal generators, signal analyzers, oscilloscopes and a stock of connectors and cables to allow for the configuration and execution of custom test designs.

## 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 made for experimenting with algorithms and informing simulation models with actual data. Scheduled to launch in 2027, Dragonfly marks the first time NASA will fly a rotorcraft for science on another world.

## MOTION TABLE FACILITY

The Motion Table Facility supports various programs for physics-based trainers, test and evaluation, and specialized concept development. The centerpiece of this lab is a Moog six-degree-of-freedom motion system that can support payloads of up to two tons for various applications. High-performance cueing algorithms provide motion fidelity that can be used for any number of concepts. This facility also serves as a staging area for advanced computer-based training technologies, including specialized virtual reality gear from commercial and government providers.

## COMMUNICATIONS CENTRAL

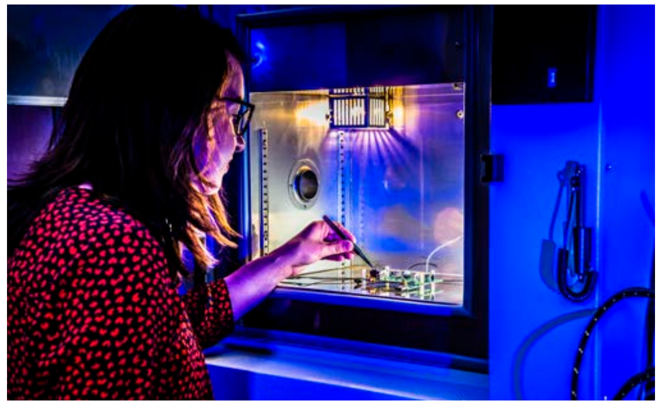
The Comms Central facilities provide a platform to test and develop the decision-making and management needed for and enabled by communication systems for missions of critical national importance. From the Command Center, our sponsors can see a mission's information flows and can asses and control the communications environment.

## 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.

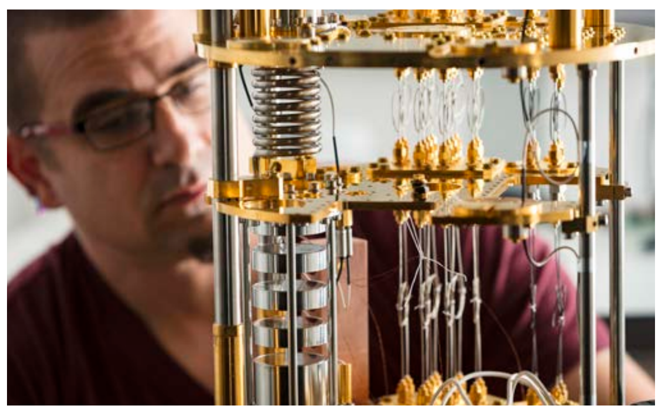
## MATERIALS FOR EXTREME ENVIRONMENTS LABORATORY

APL develops mission-critical systems for the extreme environments of 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, we use innovative formulations and processing techniques, as well as unique testing, to enhance material performance and survivability — and create mission-engineered materials to enable critical capabilities.



## THE EXPERIMENTAL COMMUNICATIONS LABORATORY

This 2,800-square-foot 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.



## QUANTUM DEVICES LABORATORY

The Quantum Devices Laboratory is a key resource for addressing critical challenges in quantum information science. State-of-the-art microwave, cryogenic and quantum control technologies enable researchers to test new theories and devices critical to harnessing the power of quantum for computing and sensors.


## INTELLIGENT SYSTEMS CENTER (ISC)

The ISC radically enhances our ability to develop algorithms and machine teammates for human operators. The center leverages APL's broad expertise across defense, intelligence, homeland protection, space exploration and health care to fundamentally advance the employment of intelligent systems in real-world settings — and in ways that benefit the nation.



## 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.

## COMBAT SYSTEMS CYBER WARFARE ANALYSIS LABORATORY

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.

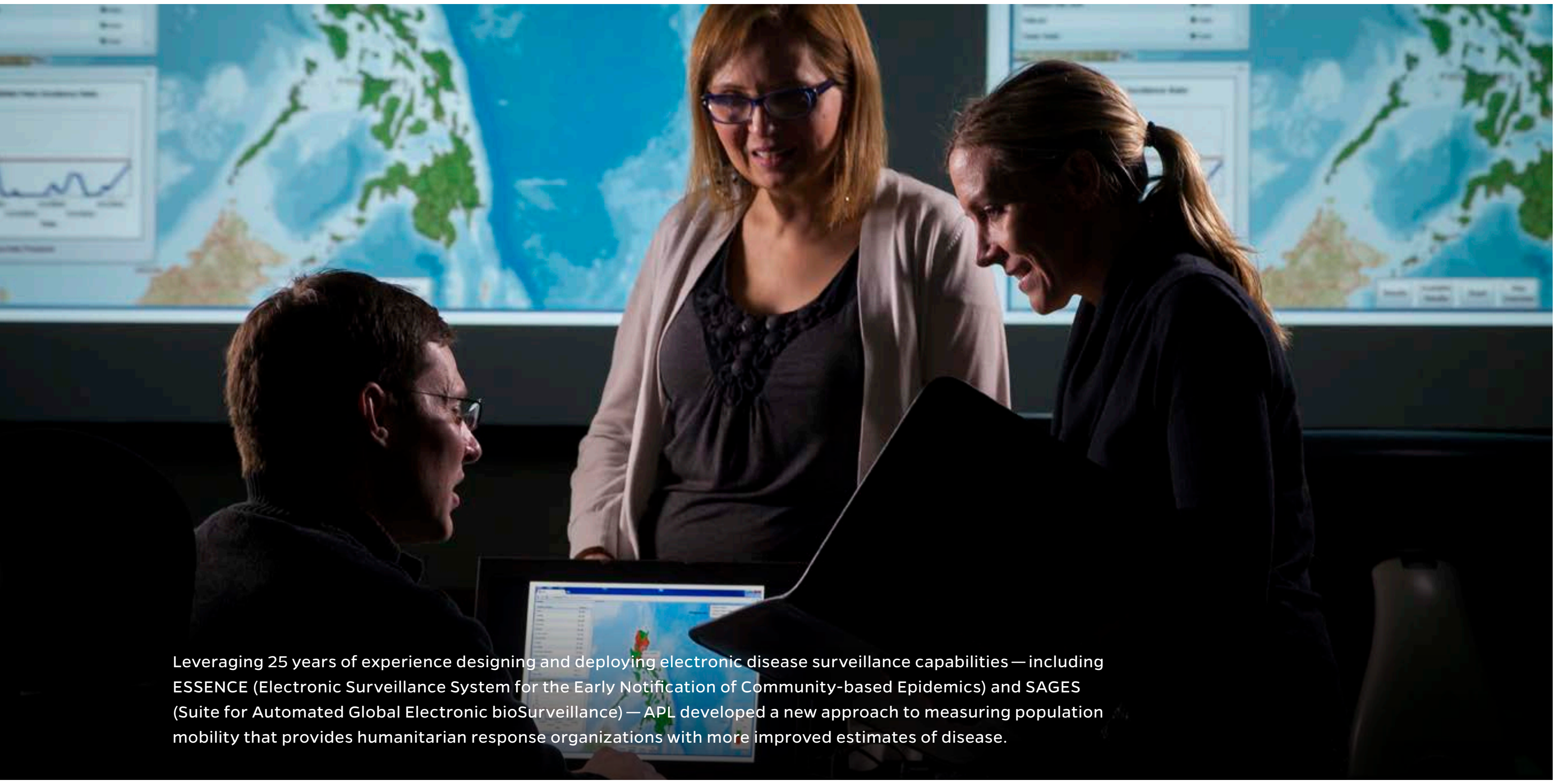
## SPACE SIMULATION AND VIBRATION TEST LABORATORIES

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. Our testing philosophy — test as you fly, fly as you test — has enabled the remarkable longevity of APL's spacecraft and instruments.

## HYDRODYNAMICS RESEARCH LABORATORY

The Hydrodynamics Research Laboratory was established decades ago to help the Navy and other government sponsors understand the phenomenology behind hydrodynamics challenges — a critical mission that continues today.

# TECHNOLOGY TRANSFER



Leveraging 25 years of experience designing and deploying electronic disease surveillance capabilities — including ESSENCE (Electronic Surveillance System for the Early Notification of Community-based Epidemics) and SAGES (Suite for Automated Global Electronic bioSurveillance) — APL developed a new approach to measuring population mobility that provides humanitarian response organizations with more improved estimates of disease.

Technology Transfer (TT) ensures the broadest possible impact of APL innovation – enhancing the reach of some of our best ideas and technologies while promoting and protecting the intellectual property (IP) our staff members develop to address the nation's most critical challenges.

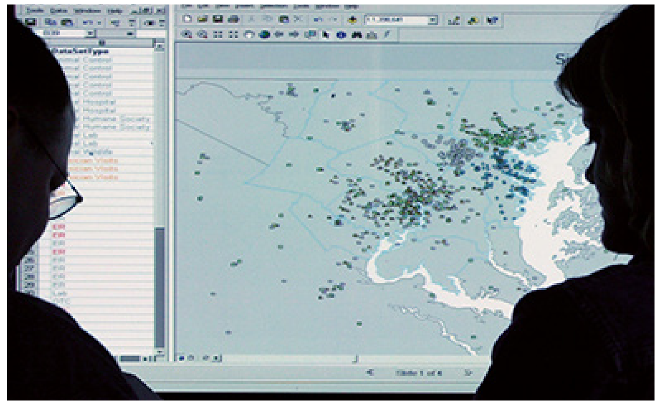
## TECH TRANSFER AND COVID-19

In fiscal year (FY) 2021, TT continued to implement strategies to incentivize the rapid utilization of the Lab's available technologies for preventing, diagnosing and treating COVID-19 infection during the pandemic.

The United Nations (U.N.) Office for the Coordination of Humanitarian Affairs (OCHA) tapped APL to adapt and operationalize Laboratory-developed epidemiological models to generate predictions of the scale of the pandemic at a sub-regional level. Leveraging these modeling solutions, OCHA is shaping its humanitarian response plans by estimating COVID-19 impacts in priority countries receiving humanitarian aid, thereby improving opportunities for future aid from the humanitarian community. TT, at the U.N.'s request, made the OCHA-APL predictive model publicly available, for free, under an open-source license to share the capability with the international humanitarian community.

Two medical supply innovations that were created by APL as a part of the Johns Hopkins University (JHU) COVID-19 Research Response Program were made available through APL's new one-click licensing website: the 3D-printed face shield and the rapid assembly stretch mask. Both solutions were developed by APL and delivered to the JHU Health System to help overcome supply shortages in hospitals at the start of the pandemic. Now, instructions for both products are publicly available to anyone interested in making their own protective equipment.

APL has entered into a license agreement with InductiveHealth Informatics for the Electronic Surveillance System for the Early Notification of Community-based Epidemics, or ESSENCE. The commercial partnership will allow InductiveHealth to offer ESSENCE to customers and provide related support and maintenance while also allowing APL staff to focus on ESSENCE-related research and development. ESSENCE, which APL began developing in 1997, has continued to modify, clean and process large amounts of health-related data. The system's algorithms search for anomalies that might indicate a COVID-19 outbreak. ESSENCE has also been used to monitor mass gatherings for indicators of disease, assist in disaster recovery efforts, screen the effects of e-cigarette/vaping and track opioid-related deaths.



APL scientists use environmental data to help predict disease outbreaks, monitor mass gatherings and assist in disaster recovery efforts.

## IP DISCLOSURES, AGREEMENTS AND START-UPS

In FY 2021, APL submitted 478 IP disclosures and entered into 65 new licenses and other agreements.

TT successfully negotiated and executed a licensing agreement with Maryland-based Harbor Designs and Manufacturing LLC for two emergency-use ventilator designs that can be produced at low cost for deployment in global crisis situations. The agreement allows Harbor to develop, manufacture and distribute ventilators based on APL's designs. The designs solve significant problems with existing portable ventilators used in acute trauma and clinical settings, particularly in economically disadvantaged areas of the world where high-end ventilators are prohibitively expensive.

APL negotiated an option agreement with Avnos, Inc., a California-based start-up that is developing a process to capture greenhouse gases from the air. Avnos is testing APL's novel adsorbent that removes water from air to verify whether it would make their capture process more efficient by drying the air first.

One start-up company based on the Laboratory's IP was created in FY 2021. EXOForce Robotics is commercializing a groundbreaking, high-quality, stretch athletic textile, developed at APL, that conforms to the body to enhance sensing performance and represents a substantial leap beyond current biometric offerings. These intelligent garments sense muscle behaviors and whole-body biomechanics, and use machine learning to tailor readouts to the wearer, quantify their workouts and alert them to impending injury. This technology has broad utility in the athletic (professional sports and consumer wellness), medical (rehabilitation and remote patient monitoring) and military markets.

TT also coordinated with APL staff members and sponsors in the U.S. Department of Homeland Security's Commercialization Accelerator Program (DHS-CAP) to promote the advancement of APL technologies into licensing agreements and new ventures. For the second year, DHS-CAP provided $150,000 to target market-development activities for APL's Centimeter Wave Holographic Imaging technology, which conducts threat surveillance, and support a pilot of APL's Autonomous Recovery from Malware/Ransomware (ARMR) software. ARMR mitigates damage to computers from cyberattacks by enabling rapid recovery of computer operating systems and data when anti-malware solutions and enterprise backups prove ineffective.

Using a stretch athletic textile developed at APL, EXOForce Robotics is creating intelligent garments that can sense muscle behaviors and whole-body biomechanics, and use machine learning to tailor readouts to the wearer, quantify their workouts and alert them to impending injury.

## NEW APL ENTREPRENEURIAL STAFF & ALUMNI PROGRAM

The APL Entrepreneurial Staff & Alumni Program (AeSAP) supports the entrepreneurial aspirations of staff members and helps expand the reach of some of APL's most commercially promising technologies. Malik Little is the second recipient of the AeSAP Archimedes Award and departed the Laboratory to launch his start-up, Enigma Science and Technology. The company will focus on Little's concept for law enforcement to wear sensors that collect physiological data during apprehension to prevent unintentional injury or arrest-related deaths.

AeSAP, which launched in December 2019, recognizes that the Laboratory can advance its primary mission to provide critical contributions to critical challenges in many ways, including commercializing IP and contributing to an innovation ecosystem of start-ups. As an Archimedes Award winner, Malik will continue to receive APL-funded benefits (such as health and dental insurance) and access to laboratory and office spaces in Johns Hopkins Technology Ventures' FastForward innovation hub and their associated entrepreneurial resources.

Malik Little is the second recipient of APL's AeSAP Archimedes Award and the founder of Enigma Science and Technology.

## NOTABLE COLLABORATIONS

APL hosted the Power on the Move event, which assembled a select group of industry and government participants to discuss innovations in battery technologies from both APL and the Johns Hopkins University Krieger School of Arts and Sciences. APL and JHU colleagues shared developments in battery chemistry and fabrication that enable unprecedented safety, performance and sustainability characteristics, and explored priorities and implications of those developments across a range of industries. Guests included representatives from Apple, Facebook, Medtronic, and Stanley Black and Decker, as well as JHU Trustee Chuck Clarvit. The event, which leveraged a prototypical approach to industry engagement at APL, has yielded several strong leads for sponsored research and licensing.

APL researchers synthesized aluminum niobate from scratch using a method that could be replicated at commercial scale, and demonstrated operation in pouch cells (seen here) — one of the main types of commercial batteries — with high energy.

From left, APL's Zhiyong Xia, Matthew Logan and Spencer Langevin have identified highly absorbent materials that can extract drinkable water out of thin air, which could potentially lead to technologies that supply potable water in the driest areas on the planet.

## INVENTION RECOGNITION

Awarded in 2021, the Laboratory's 2020 Invention of the Year went to Spencer Langevin, Matt Logan, Scott Shuler and Zhiyong Xia for the Atmospheric Water Harvesting Device. The team invented a highly adsorbent specialty material composed of a combination of hydrogel and a modified metal organic framework that is effective at extracting water from the humidity in air. This engineered adsorbent has been manufactured, tested and proven to have the ability to effectively extract water from air.

## STATISTICALLY SPEAKING — FY 2021 DATA FOR TT

**478** IP assets disclosed*

**25** U.S. patents issued

**105** U.S. provisional patent applications filed

**25** U.S. nonprovisional patent applications filed

**65** license agreements executed

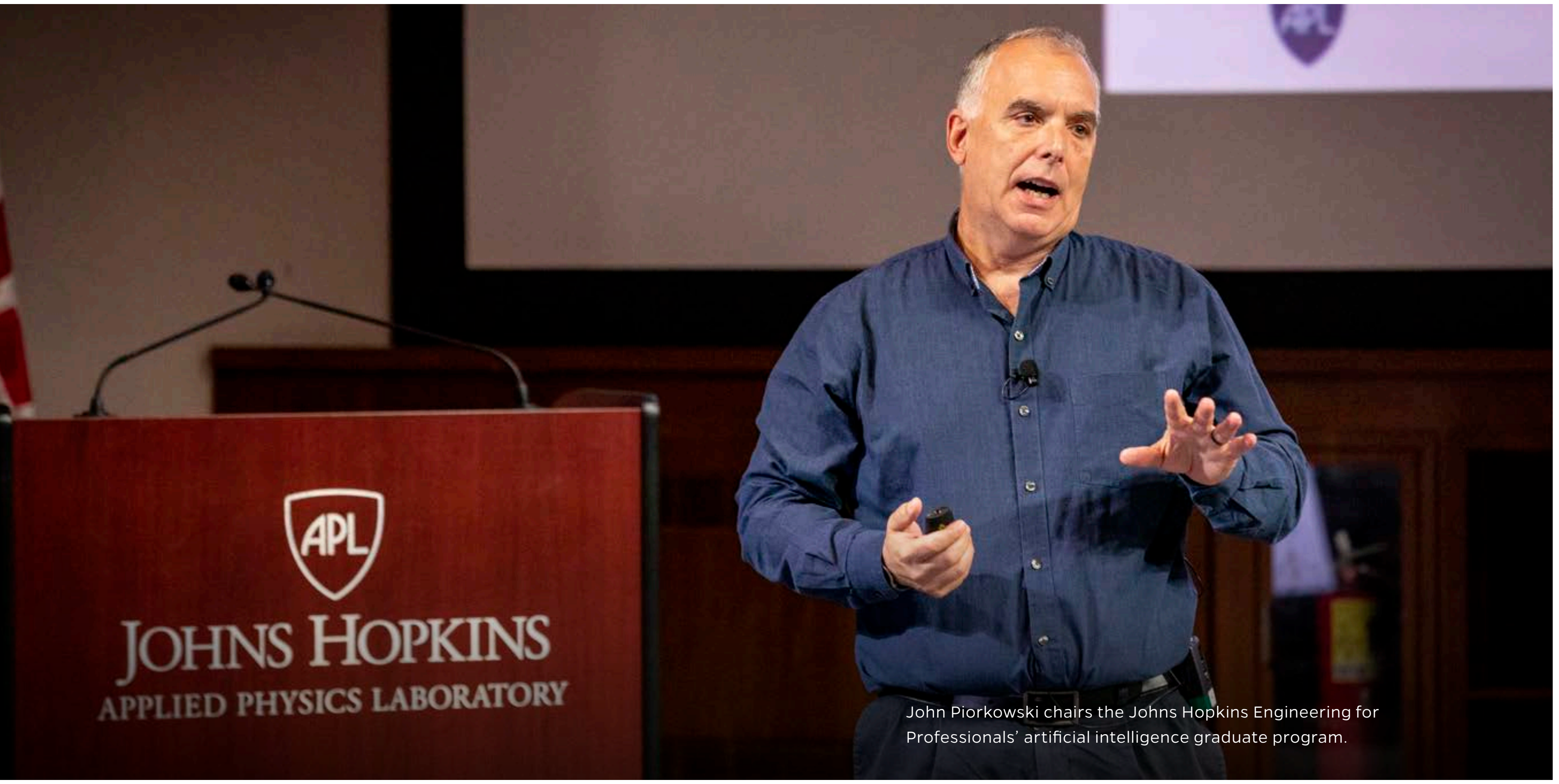
**1** new company created

*An APL record

## 2021 R&D 100 AWARD

APL provided expertise critical to the development of a fieldable nuclear threat assessment instrument that was selected as a winner of the 2021 R&D 100 Awards. The award-winning device, the Multiplicity Counter for Thermal and Fast Neutrons (MC-TF), is a field-deployable tool that first responders can use to quickly assess, in real time and with high confidence, the threat level posed by a suspected nuclear weapon.

# UNIVERSITY COLLABORATIONS




John Piorkowski chairs the Johns Hopkins Engineering for Professionals' artificial intelligence graduate program.

**As a university affiliated research center and research division of Johns Hopkins University (JHU), APL has a unique opportunity to make the world healthier, safer and more secure.**

With our colleagues across the institution, we collaborate to tackle a variety of challenges and missions in health, engineering, science and security analysis. These interdisciplinary partnerships include the Johns Hopkins Hospital, the Whiting School of Engineering, the School of Medicine, 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.

## ENGINEERING FOR PROFESSIONALS

In 2021, more than 350 APL staff members taught engineering, applied science, engineering management, technical management and information technology courses within the Johns Hopkins Engineering for Professionals (EP) program. Twenty APL staff members also serve as chairs, vice chairs or program managers for 12 of EP's 22 master's degree programs, with the most recent appointment being David Silberberg. Silberberg was appointed chair of the Information Systems Engineering program. The EP artificial intelligence graduate program, chaired by John Piorkowski, has grown significantly and is now preparing more than 350 students for the major challenges of today's information technology world. At the start of shutdown and stay-at-home orders due to the COVID-19 pandemic, the EP program was already offering over 93% of its courses online, enabling a smooth and quick transition to an all-remote learning environment. In 2021, the online percentage reached 97%, and the course enrollments in the APL-based programs accounted for 84% of the total EP course enrollment of 16,352. The number of students enrolled in the APL-based programs accounted for 85% of the total students (7,100) enrolled in the EP program, and 103 of 111 APL staff members who graduated from the program received degrees from APL-based programs.

## DOCTORATE OF ENGINEERING PROGRAM

APL staff members helped pilot the Whiting School of Engineering's doctor of engineering (D.Eng.) program, designed with the needs of working, mid-career engineering professionals in mind. D.Eng. candidates, who hold master's degrees before entering the program, have three years to obtain their doctorates while under the guidance of a faculty advisor. The D.Eng. program is application-based, focusing on engineering advances such as prototypes, inventions and new software that can help students meet professional goals and immediately contribute to their current job responsibilities. In 2021, 33 students, 25 of whom were APL staff members, were enrolled in the D.Eng. program. In May 2021, Bart Paulhamus, Myron Brown, Jeffrey Chavis and Peter Thielen became the first four APL graduates of the program. They were followed at the end of the summer by Kara Shipley and Jennifer McKneely. Karl Siil graduated in December 2021.

Bart Paulhamus (left) and Jeffrey Chavis pose for a photo after Johns Hopkins University's doctoral program commencement ceremony in 2021. Paulhamus and Chavis were two of the four APL staff members in the first graduating class of the new doctor of engineering program. (Credit: Jeffrey Chavis)

## DISCOVERY AWARDS

Launched in 2015 to spark collaborations across JHU that promise to result in high-quality and impactful work, the Johns Hopkins Discovery Awards program attracted a record 274 proposals — each composed of members from at least two Johns Hopkins divisions — in 2020. From these proposals, 41 teams received awards of up to $100,000 to conduct work in FY 2021. Three principal investigators from APL were among the researchers chosen for the sixth round of Discovery Awards. The APL-led projects investigated aspects of public health messaging most likely to persuade individuals to take behavioral action, such as getting a COVID-19 vaccine; developed an inexpensive disease diagnostic and surveillance tool based on daily blood sugar monitoring; and used tools from differential geometry to better understand and detect unconscious bias training in artificial intelligence. Another nine staff members were on research teams that received Discovery Awards.

Jennifer McKneely (left) and Adam Crego are working with Rupali Limaye of the Bloomberg School of Public Health on a Johns Hopkins University's Discovery Awards project to combine neuroscience techniques with self-report measures to identify aspects of public health messaging that will most likely persuade an individual to take action. The blue mannequin head illustrates functional near-infrared spectroscopy combined with eye-tracking technology.

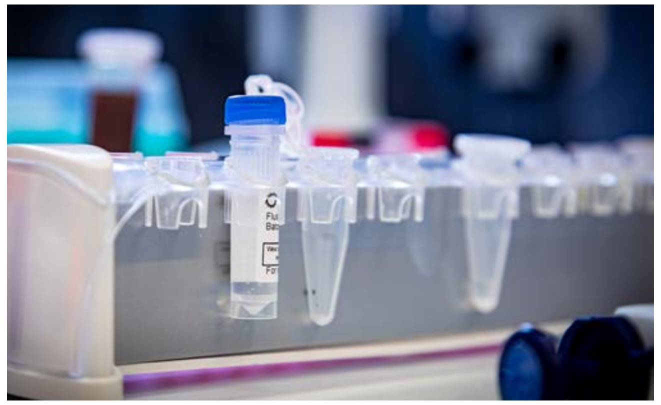
## RISE AT APL

The prestigious and competitive Research Internships in Science and Engineering (RISE@APL) program is open to highly qualified undergraduate and graduate students from a number of JHU schools. It provides students with the opportunity to conduct research at APL on a variety of topics, including ballistic missile systems, prosthetics, computer vision and secure mobile communications.

The Johns Hopkins Whiting School of Engineering. (Credit: JHU)

## COVID-19 RESPONSE

The rapid growth of the COVID-19 pandemic drove a massive demand for the data—because there was nothing like it available yet. Epidemiologists from Johns Hopkins and data scientists from APL teamed up with the JHU Center for Systems Science and Engineering and Co-Director Lauren Gardner to build the COVID-19 Dashboard, now considered the definitive resource for epidemiologists, elected officials, public health leaders, media and the general public around the world to track the outbreak. Collaborations between experts across the enterprise also helped scientists and healthcare workers better understand the growth and progression of the disease. Early on, an effort by scientists from across Johns Hopkins University and Health System to sequence the genome of SARS-CoV-2, the virus causing COVID-19, produced a study characterizing the early introduction of the virus into the National Capital Region. The research also provided information about the progression of cases as quarantine procedures were implemented, and ways to study the efficacy of an eventual vaccine. Prior to COVID-19 emergence, APL collaborated with the National Institutes of Health Fogarty International Center to establish sequencing capabilities in low- and middle-income countries. These engagements began as part of our NIH-funded Johns Hopkins Centers of Excellence for Influenza Research and Surveillance (CEIRS), where we performed near real-time analysis of seasonal influenza viruses and SARS-CoV-2 from within Johns Hopkins Health System to better understand global virus evolution and its impact on medical countermeasures. APL researchers developed basic sequencing protocols, an open-source software platform (BaseStack) that simplifies complex bio-informatics processes, and an exhaustive training program.



Collaborations between experts across the Johns Hopkins University enterprise helped scientists and health care workers to better understand the growth and progression of SARS-COV-2, the virus that causes COVID-19.

The package allows any laboratory in the world to sequence viruses in its local region—revolutionary accessibility. We led six workshops, reaching more than 200 trainees from 14 countries across Asia, Africa, and North and South America. Participants in those workshops have used the APL-developed BaseStack framework to identify SARS-CoV-2 variants, such as the B1.1.7 strain (first classified in the U.K. and among the three the CDC warned about) in travelers who had recently arrived from other countries. All of those efforts will be on display in a newly expanded partnership with the CEIRS program. A multidisciplinary team of APL researchers will combine SARS-CoV-2 genome sequences with detailed patient data, such as status and laboratory testing, to correlate regional COVID-19 transmission dynamics and patient outcomes in the National Capital Region. This two-year study will enable physicians and scientists to understand how the virus changes over time, and relate the impact of those changes on virus spread, case incidence and disease severity.

## APL PARTNERS WITH CDC TO PROTECT FRONTLINE HEALTH CARE WORKERS

APL, in collaboration with the Johns Hopkins Armstrong Institute for Patient Safety and Quality, undertook a two-year study sponsored by the Centers for Disease Control and Prevention (CDC) to conduct an extensive characterization and analysis of aerosol generation in health care settings with the goal of reducing the exposure of frontline health care workers and patients to potentially infectious aerosols. The effort is part of Project Firstline, a CDC initiative aimed at training and empowering every member of the U.S. health care workforce with the infection control knowledge to implement actions that protect themselves, their facility and their community. While clearly valuable for the current COVID-19 response, Project Firstline addresses the ongoing need for infection control training, education and innovation for the wide array of routine infectious risks encountered every day in health care settings. APL is leveraging its extensive capabilities in aerosol science, biology and miniature sensors on one of the most crucial tasks in this effort: characterizing air and aerosol movement in clinical environments.

APL is using a combination of advanced sensing approaches to develop solutions to minimize the negative effects of air movement for patients and health care personnel.

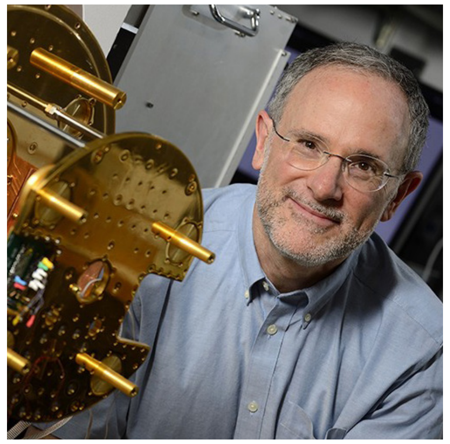


## BLOOMBERG DISTINGUISHED PROFESSORS

Bloomberg Distinguished Professors bridge JHU's academic divisions and enable innovative research that crosses traditional disciplinary boundaries. Three Bloomberg professors hold joint appointments with APL. Sabine Stanley, a professor in the Krieger School of Arts and Sciences' Department of Earth and Planetary Sciences with a joint appointment in APL's Space Exploration Sector, is an eminent planetary physicist focusing on magnetic fields as a means of studying the interiors of planets, including those in little-understood realms light years away from our solar system. Michael Tsapatsis, a tenured professor in the Whiting School of Engineering's Department of Chemical and Biomolecular Engineering with a joint appointment in APL's Research and Exploratory Development Department, is a renowned materials scientist whose groundbreaking work has had tremendous impact across the research community, industry and society. Charles Bennett, a professor of physics and astronomy at the Krieger School of Arts and Sciences and senior scientist in the Laboratory's Space Exploration Sector, is a renowned researcher in experimental astrophysics and cosmology who focuses on extending our understanding of the universe by observing the cosmic microwave background.

Sabine Stanley (Credit: JHU)

Michael Tsapatsis (Credit: JHU)



Charles Bennett (Credit: JHU)

## INSTITUTE FOR ASSURED AUTONOMY

With an internal commitment of $30 million, JHU launched the Institute for Assured Autonomy (IAA), a national center of excellence focused on ensuring that autonomous systems can be trusted to operate as expected, respond safely to unexpected inputs, withstand corruption by adversaries and integrate seamlessly into society. The program is co-led by APL and the Whiting School of Engineering. In 2021, Jim Bellingham, a pioneer in the worldwide autonomous marine robotics field who has led research expeditions from the Arctic to the Antarctic, was appointed executive director of the IAA. For more than 30 years, Bellingham has been a global leader in the development of small high-performance autonomous underwater vehicles, resulting in a class of systems that are now widely used within the military, industry and scientific communities. Bellingham concurrently serves as a research professor in the Whiting School's Department of Mechanical Engineering and as a senior advisor in APL's Asymmetric Operations Sector, where he helps advance government and defense innovations for national security.

## CIRCUIT

The Cohort-based Integrated Research Community for Undergraduate Innovation and Trailblazing, or CIRCUIT, aims to help high-potential Johns Hopkins students overcome barriers to STEM careers. In 2021, the program assisted 70 students on 15 projects in six mission areas. Projects incorporate two to five students working together to solve an important research or sponsor challenge, ranging from undersea to outer space domains, and including major activities in artificial intelligence and robotics. Mentors work with students throughout the summer, and during the fall and spring semesters, in parallel with the training and mentoring activities provided by the program. APL's Will Gray Roncal of the Research and Exploratory Development Department (REDD) leads the program, and Martha Cervantes, also of REDD, serves as project manager.

# 10 YEARS OF STEM


A group of students and an APL volunteer show off their creation from a 2019 MESA Elementary Interactive STEM Day event.

## APL's STEM Program Management Office (PMO) turned 10 in 2021, and there was a lot to celebrate about the decade of dedicated efforts to develop science, technology, engineering and math talent.

The Lab did conduct a smaller number of science, technology, engineering and math outreach programs before 2011, but that's when APL decided to take a strategic approach to expanding its contributions to the STEM community and leverage its resources to increase its impact. Program Manager Dwight Carr and volunteer Brian Duncan reflected on the evolution of the Lab's STEM programs since the PMO's inception.

### EVANGELIZING STEM

In his first few years on the job, Carr focused on evaluating existing efforts, determining strengths, identifying gaps and staffing the office to reach its goals. He did all this and more with a passion that continues today.

"It's a personal mission to make sure that I'm evangelizing STEM in some way; to make sure everyone knows about this career path, and that they have an opportunity to contribute and ultimately change the world through STEM," Carr said. When he was growing up, neither he nor his parents had a clear understanding of STEM as a career path, so he wants to bring that knowledge to kids — especially those who might not know about it.

APL STEM Program Officer Dwight Carr helps a student at a 2017 STEM event at Walter Reed National Military Medical Center in Bethesda, Maryland.



APL's STEM program office launched in 2011, but the Lab's commitment to educational outreach goes back decades, including student tours like this one from 1977.

Attendees engage with a volunteer during the 2015 Girl Power Expo at APL's Kossiakoff Conference and Education Center.

APL's STEM program comprises MESA (Math, Engineering, Science Achievement), STEM Academy and ASPIRE (APL's Student Program to Inspire, Relate and Enrich), as well as community outreach efforts such as the Girl Power expo, College Prep Program and High School Cybersecurity Summer Workshop.

MESA is an after-school program for students in grades 3 through 12; STEM Academy offers enrichment courses to students in grades 8 through 12; and ASPIRE is a hands-on internship for students in grades 11 and 12. While MESA and ASPIRE began in 1976 and 1988, respectively, STEM Academy was established in 2017 under Carr's watch. He also expanded MESA and ASPIRE, making them more accessible.

Since 2013, the STEM PMO has awarded $25,000 in scholarships to students who have participated in MESA, STEM Academy or ASPIRE. Four students per program are each awarded on average $2,000 annually. Former APL staff member Karl Kostoff bequeathed the scholarship funds to the Lab.

### PERSONAL CONNECTIONS

The STEM PMO has also hosted special projects with the National Science Foundation, NASA and the Office of Naval Research (ONR). Carr's favorite such event, called CONVEY, was funded by ONR and aimed to see if students would be more likely to pursue STEM careers if they could see how STEM benefits someone in their lives.

Carr organized a workshop focused on neuroscience and prosthetics for children of injured service members. The event included hands-on demonstrations with APL's Modular Prosthetic Limb and incorporated virtual and augmented reality technology. Carr fondly remembers one of the students, a girl whose father had lost his leg, saying after the workshop that she wanted to go into STEM to help fix her dad's leg.

Carr credits the staff members working in the office, the many volunteers and APL leadership for contributing to the program's success. "I work with a really talented group of people, and without that team, there's no way we could have worked with over 35,000 kids, awarded over $200,000 in scholarships and reached over 800 teachers," he said.

All the metrics prove that the STEM programs are successful, but Carr believes it's the stories between the data points that paint the true picture of the programs' impact and efficacy. Many students have shared with Carr that without MESA, STEM Academy or ASPIRE, they wouldn't have known about STEM career opportunities or had the experiences that opened doors to their future.

Carr is especially moved when he hears from students who say the programs changed their trajectory in life. Similarly, he recognizes that representation is important and emphasizes this within the programs. Because people of color are underrepresented in STEM, he hopes that if students see STEM professionals who look like them, they can focus on developing their identity as a STEM professional instead of feeling as if they don't belong.

With a decade of steady growth under its belt, APL can start to see how its STEM programs have shaped lives, evidenced, in part, by students who participated in the programs returning to the Lab as staff members. Each year, many of the Lab's college interns have had some engagement in the Lab's STEM activities. And every year since 2016, the Lab has welcomed new staff members who were former STEM program students.

## SHARING A PASSION

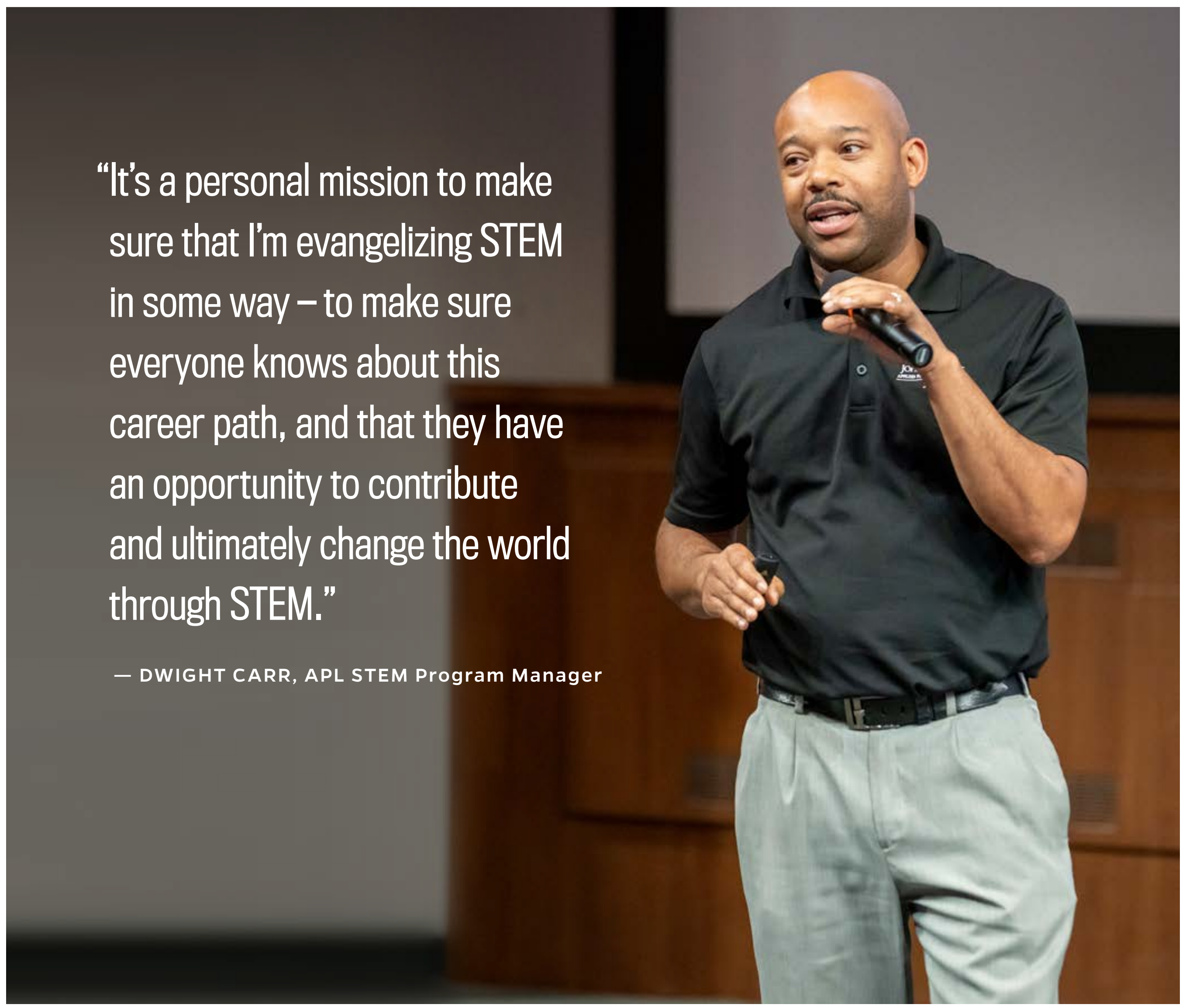
Carr said he's equally proud of the relationships built with the volunteers. "When I started in this role, I didn't know how much support I would have," he recalled. "But they're passionate about it; they give 110% every time."

Duncan, a branch supervisor in the Space Exploration Sector, is one such volunteer. He first served as a mentor for ASPIRE students and represented the Lab at job fairs at local schools; from there he became an assistant instructor for STEM Academy and is now a primary instructor, having recently developed an entirely new course for the program.

One factor in the programs' success over the past decade is what Carr has dubbed the "un-school method" of instruction. This approach ensures the programs are fun, engaging and purpose-driven. In STEM Academy, for example, the instruction is project- and situation-based, meant to mirror work at APL as much as possible. Activities are based on a fictitious sponsor request, which the kids and instructors work together to fulfill.

Duncan echoed Carr's emphasis on practical, hands-on instruction being key to keeping kids' interest. While he could teach them the basics of programming, he prefers to frame it in a real-world context so that students understand how these skills can be applied.

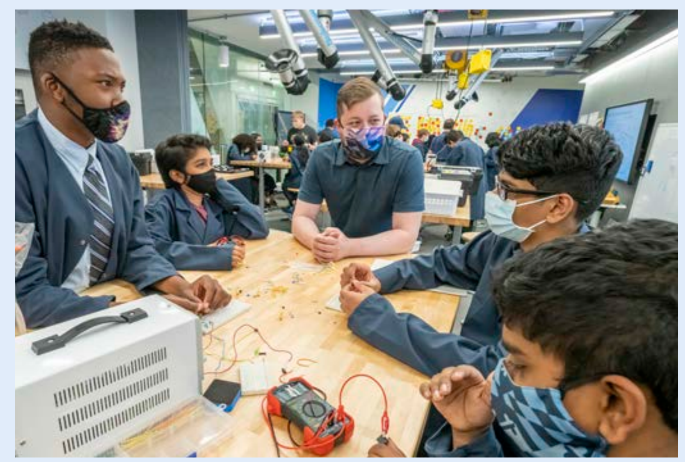
"The most rewarding thing for me is when they really stick with it," Duncan said. "When they present their projects at the [semester-ending] STEM Expo, they've done these wonderful things and they're beaming with pride. They show everybody their code and they run their program — it's this imaginative transformation."



"It's a personal mission to make sure that I'm evangelizing STEM in some way – to make sure everyone knows about this career path, and that they have an opportunity to contribute and ultimately change the world through STEM."

— DWIGHT CARR, APL STEM Program Manager


In 2021, APL opened a brand-new STEM Center in Building 201 that includes flexible, interactive classrooms with thoughtful, student-centered design.



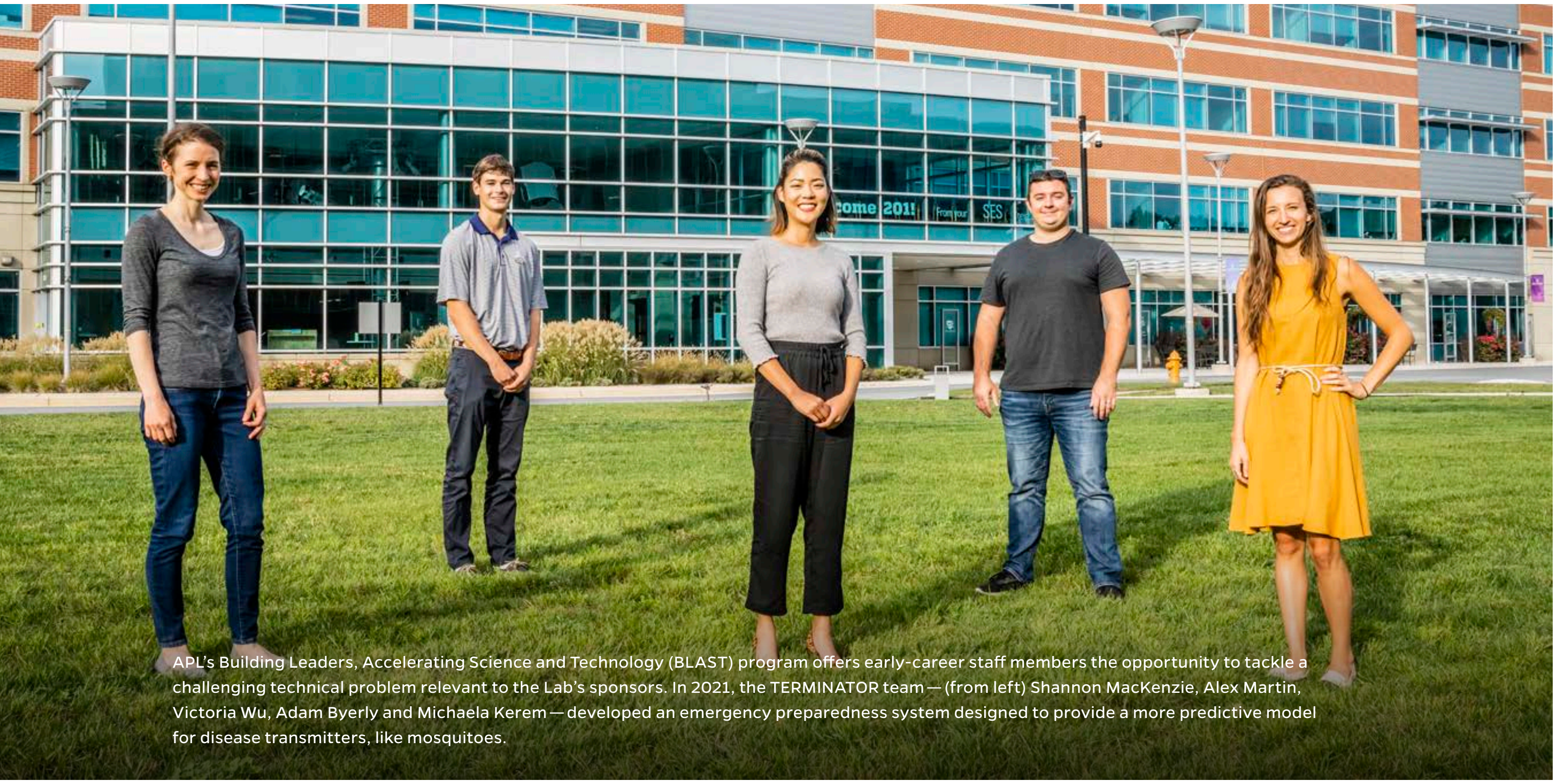
## THE NEXT DECADE – AND BEYOND

What will the next 10 years look like for the STEM PMO? For starters, students will get to take advantage of learning in the program's brand-new STEM Center in Building 201. The center includes flexible, interactive classrooms with thoughtful, student-centered design. Because the building is outside of the security perimeter, Carr hopes it will increase access for even more students.

But it's not just the new learning spaces that have Carr excited and optimistic — he sees a bright future for the entire pathway of programs.

"There will always be a need for APL to be a leader in STEM outreach to help prepare future generations of the nation's STEM talent," he said. "I'm going to focus on continuing to build and grow relationships with educators, students and volunteers to make STEM accessible to all. The end goal is that students will be inspired in true APL fashion to — in the words of APL Director Ralph Semmel — 'be bold, do great things and make the world a better place.'"

# A CULTURE OF INNOVATION



APL's Building Leaders, Accelerating Science and Technology (BLAST) program offers early-career staff members the opportunity to tackle a challenging technical problem relevant to the Lab's sponsors. In 2021, the TERMINATOR team — (from left) Shannon MacKenzie, Alex Martin, Victoria Wu, Adam Byerly and Michaela Kerem — developed an emergency preparedness system designed to provide a more predictive model for disease transmitters, like mosquitoes.

From a multitiered grant system and robust research and leadership development programs to leading-edge collaboration initiatives and workspaces, APL fuels creativity and new ideas at every level.

At APL, we base our approach to innovation on the simple premise that the next game-changing concept could come from anyplace — or anyone — at the Laboratory. To ensure APL is able to support the exploration of our staff members' great ideas (and even some that ultimately do not turn out to be great), our long-standing internal funding and collaboration initiatives help our researchers come together and push the boundaries of what is possible.

The Independent Research and Development (IRAD) program is one cornerstone of innovation at APL. These investigations, proposed by staff members as individuals or as teams, are focused on strengthening APL's technical competencies and our national defense research capabilities through basic and applied research, system and concept formulation studies, and development — as well as the dissemination of results of that work. IRADs have often matured into technologies or contributions that have successfully addressed ongoing sponsor challenges. Funded IRAD projects are selected annually by mission area leadership on the basis of research relevant to those particular domains.

In addition to IRADs, the Laboratory operates additional successful innovation initiatives that provide funding, facilities and guidance to staff members seeking to explore ideas, undertake collaborative efforts and further our nation's science and engineering prowess.

## BLAST

When the Laboratory recognized a need several years ago to more heavily involve new, early-career staff members in established collaboration and innovation ecosystems, the BLAST program — short for Building Leaders, Accelerating Science and Technology — was born. What began as a small initiative launched in one APL sector has expanded across the entire Laboratory, offering 40 early-career staff members the opportunity to tackle a challenging technical problem relevant to APL's sponsors.



Each summer, BLAST participants work on a technical problem with a group of other teammates with whom they have not previously worked, and who bring different sets of skills and backgrounds. While learning to manage a project from start to finish, including budget management, participants develop relationships with peers as well as senior staff members, who serve in advisory roles and as judges at the end of each project. During 2021, the challenge was to identify, develop and demonstrate a novel solution to ensure operational resilience despite challenges related to climate change.

## PROJECT CATALYST

Project Catalyst is a Labwide grant program comprising three internal funding opportunities for APL staff members advancing high-risk, transformative ideas. Funded ideas 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. Teams post ideas online for peers to provide feedback and suggestions for improvement before a Lab-wide crowdsourced voting process determines the winners.
- **Combustion Grants** fund visionary ideas that are high risk but show promise for solving a sponsor's challenge. A panel of APL peer reviewers selects the winning proposals.
- **Propulsion Grants** support the search for game-changing solutions to significant challenges facing our nation. Projects can span multiple years, with recipients competing to earn subsequent funding.

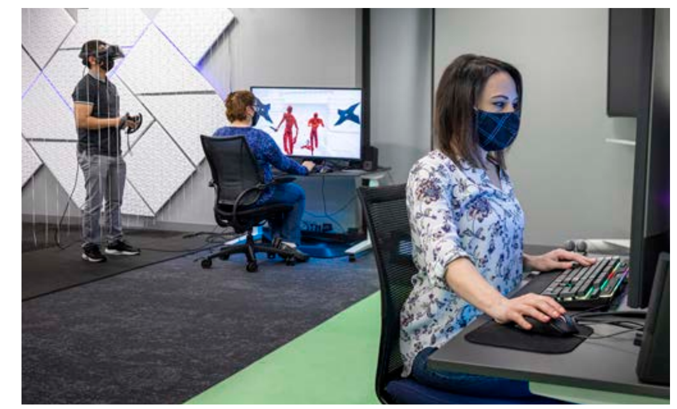
## JANNEY PROGRAM

Named for longtime Johns Hopkins University and APL board chair and member Stuart Janney, the Janney program includes four tracks — Explore, Engage, Energize and Elevate — for staff members to pursue new ideas in emerging technology, enhancing APL's position at the center of a vibrant innovation ecosystem beyond our campuses. The program complements APL sector and department education and training funds.

In 2021, the Janney program invested in staff members establishing themselves and the Laboratory as thought leaders in the engineering and scientific communities.

- **Explore** supports APL staff members who attend conferences in emerging technical areas that could prove valuable to current or future sponsor challenges.
- **Engage** backs staff member efforts to host a conference at APL, to share the Lab's impact with the broader community.
- **Energize** supports staff members who share their expertise with the community by presenting a keynote speech, delivering a TED talk-type of major presentation or even writing a book that could be valuable to the Laboratory's mission.
- **Elevate** encourages staff members to apply for leadership positions and awards in — and to aspire to be elected fellows in — key national and international technical professional societies.

## CENTRAL SPARK



APL's new Central Spark innovation facility provides more than 9,000 square feet of collaboration space and equipment for makers from every part of the Laboratory.

Central Spark is the Laboratory's open, collaborative space for makers, tinkerers and ideation. 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 almost tripled its footprint in 2020 with a move to a fully renovated 9,000-square-foot space, and Central Spark 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. The maker space also lends itself to the creation of organic networking opportunities within the Lab.

Conceived in 2014 by merging two visionary Ignition Grant ideas, Central Spark garnered the support of APL Director Ralph Semmel, who encouraged the creation of a space dedicated to enabling and supporting staff members' innovation efforts. Central Spark continues to capture the attention of users within and outside APL and has served as the launch pad for a number of inventions and concepts developed for our sponsors.

# AWARDS AND HONORS


**1.** For the third consecutive year, APL was named one of Fast Company's Best Workplaces. The Lab was ranked No. 17 on the Best Workplaces for Innovators list. For the second time, an APL group was recognized as an Innovation Team of the Year for their work on the Johns Hopkins Coronavirus Resource Center and its COVID-19 dashboard.

**2.** For the fourth year in a row, APL made the Insider Pro and Computerworld "Best Places to Work in IT" list, moving up to No. 10 in the rankings. The Lab was celebrated for its inclusivity, including its vibrant work culture, strategic mentoring program and internship programs.

**3.** The Multiplicity Counter for Thermal and Fast Neutrons (MC-TF), a fieldable nuclear threat assessment instrument jointly developed by APL, Radiation Monitoring Devices (RMD) and Lawrence Livermore National Laboratory, was selected as a winner of the 2021 R&D 100 Awards from R&D World Magazine.

**4.** David Van Wie (right) was awarded the 2021 von Kármán Lectureship in Astronautics from the American Institute of Aeronautics and Astronautics. (Credit: American Institute of Aeronautics and Astronautics)

**5.** Robert Stoll received the 2021 William Deso Excellence in Program Management Award from the Department of Homeland Security Science and Technology Directorate for his work to address biothreat challenges.

**6.** George Ho was selected to serve on the U.S. National Oceanic and Atmospheric Administration's (NOAA) Space Weather Advisory Group (SWAG).

**7.** In formal recognition of his significant contributions to the industrial hygiene field, Dan Anna was named an American Industrial Hygiene Association (AIHA) fellow.

**8.** Six APL staff members were honored with Black Engineer of the Year Awards. Clockwise from top left: Mika Ayenson, Malik Little and Justin McGrath received Modern Day Technology Leaders awards. Jamie Arribas Starkey-El received the Science Spectrum Trailblazer award, Makita Phillips received the Dr. Sandra Johnson Legacy award, and Adam Freeman received the Outstanding Technical Contribution award.

**9.** Parvathy Prem was presented with the Susan Mahan Niebur Early Career award by the Solar System Exploration Research Virtual Institute.

**10.** The APL Achievement Awards went virtual for the second consecutive year to celebrate a record 724 staff members nominated in 134 entries for 32 different awards. A record 185 staff members were recognized as winners for their 2020 accomplishments.

**11.** The Parker Solar Probe team earned the National Space Club and Foundation's Nelson P. Jackson Award, which recognizes the most outstanding contribution to aerospace in the preceding year.

**12.** Elizabeth "Zibi" Turtle was awarded the inaugural Claudia J. Alexander Prize by the American Astronomical Society's Division for Planetary Sciences for her integral role in analyzing and interpreting images from the Galileo and Cassini missions.

**13.** The APL Women in Technology affinity group earned its third consecutive Gold Mission award from the Society of Women Engineers for demonstrated commitment to the society's goals of professional excellence, globalization, advocacy, and diversity and inclusion.

**14.** Danielle Hilliard was awarded an Advocating Women in Engineering award by the Society of Women Engineers.

**15.** APL's first publication related to Climate TRACE earned the award for Best Paper in the EarthVision Workshop track at the 2021 IEEE Conference on Computer Vision and Pattern Recognition. From left: Gordon Christie, Ryan Mukherjee, Derek Rollend and Anshu Saksena. Not pictured: Marisa Hughes, Sally Matson and Armin Hadzic.

**16.** Graeme Smith was named an associate editor of the journal IEEE Transactions on Aerospace and Electronic Systems.

**17.** Vijitha Weerackody was appointed a senior editor of the journal IEEE Transactions on Aerospace and Electronic Systems.

**18.** Morgan Trexler received a SWE Patent Recognition award from the Society of Women Engineers. She was also named to the Hopkins Extreme Materials Institute executive committee.

**19.** Three APL principal investigators — (from left) Jennifer McKneely, Adam Crego and Dan Siegal — received funding from the Johns Hopkins Discovery Awards program, which was launched in 2015 to spark collaborations across the university that promise to result in high-quality and impactful work.

**20.** Five APL staff members — (clockwise from top left) Latise Baker, Cara Hall, Karmethia Thompson, Suman Woolums and Shahnaz Ukani — were honored in October with Women of Color STEM awards for their commitment to mentoring and encouraging women in STEM fields.

**21.** Mary Lasky received the Linda Franklin National Achievement Memorial award for her longstanding leadership in national disaster resilience.

**(Not pictured)** The Lunar Surface Innovation Consortium (LSIC) team received NASA Headquarters' 2020 Honor Award — its highest form of recognition — for the team's outstanding contributions to the agency's mission.

**(Not pictured)** The Metropolitan Washington Council of Governments — using the APL-developed data modeling tool Dagger to build a regional capability for monitoring health care resource utilization during the COVID-19 pandemic — won a 2021 Solutions Award from the Computer Technology Industry Association (CompTIA) Public Technology Institute (PTI).

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Assistant Director, Science and Technology; Chief Technology Officer

**Lisa Blodgett**
Head, Force Projection

**Donna Gregg**
Head, Asymmetric Operations

**Aili Kujawa**
Head, Talent Services; Chief Diversity and Inclusion Officer

**Nick Langhauser**
Head, Business, Construction and Facilities; Chief Financial Officer

**Michael Misumi**
Head, Information Technology Services; Chief Information Officer

**Leonard Moss**
Head, Security Services; Chief Security Officer

**Paul Oostburg Sanz**
General Counsel

**Emelia Probasco**
Head, Communications; Chief Communications Officer

**Mike Ryschkewitsch**
Head, Space Exploration

**Matthew Schaffer**
Head, National Security Analysis

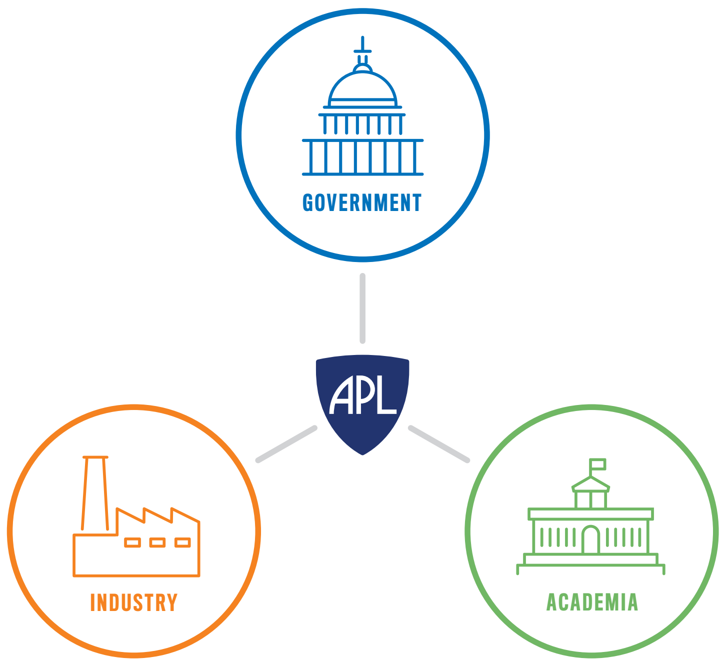
**Jim Schatz**
Head, Research and Exploratory Development

**Dave Van Wie**
Head, Air and Missile Defense

# ABOUT UARCS

"[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, including proprietary data
- Broad corporate knowledge
- Independence and objectivity
- Quick response capability
- Current operational experience
- Freedom from real or perceived conflicts of interest

## AS A UARC, APL IS A 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 systems 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.

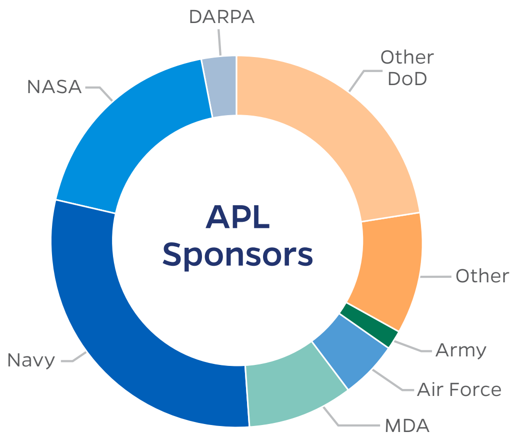
The majority of our work comes from the Department of Defense as sole-source (noncompetitive) funding under the Competition in Contracts Act, primarily through the exception for essential research and engineering.



# FINANCIAL STATEMENT

During the fiscal year that ended September 30, 2021, the Johns Hopkins Applied Physics Laboratory recorded revenue from contracts and grants totaling $1.91 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.

**FY21 Revenue: $1.91 Billion**





## APL'S MISSION IS TO MAKE CRITICAL CONTRIBUTIONS TO CRITICAL CHALLENGES.

**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 2021, we had:**

- 140 different government sponsors
- 119 subcontracts to 48 different universities

# APL FIELD OFFICES

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

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

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

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

**Raleigh**
The Forum, Building I
8601 Six Forks Road
Raleigh, NC 27615

APL staff members were observing COVID-19 protocols when the images were taken.

Please note that the appearance of U.S. Department of Defense (DoD) visual information does not imply or constitute DoD endorsement.

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JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

## 4.5 inches thick

Parker Solar Probe's 4.5-inch-thick heat shield of carbon composite foam, topped with reflective ceramic paint, protects the probe's onboard electronics.

READ MORE ON PAGE 23.

## 500,000 square feet

Adding almost 500,000 square feet of research, experimentation and work space, APL's three new facilities position the Lab to remain at the forefront of science and technology.

READ MORE ON PAGE 42.

## 500 simulations

The APL-built modeling and simulation environment, the virtual Colosseum, enabled rapid integration of intelligent weapon concepts, executing and processing nearly 500 simulations over a three-day span.

READ MORE ON PAGE 8.

## 140 gov. sponsors

In 2021, APL had 140 different government sponsors.

READ MORE ON PAGE 72.

## 54,000 to 62,000 miles

SMART Nav will see the DART spacecraft through a stretch of some 54,000 to 62,000 miles and ensure that it collides with its asteroid target, Dimorphos.

READ MORE ON PAGE 6.

## 478 IP disclosures

In FY 2021, APL submitted 478 IP disclosures and entered into 65 new licenses agreements.

READ MORE ON PAGE 54.

## 100% success rate

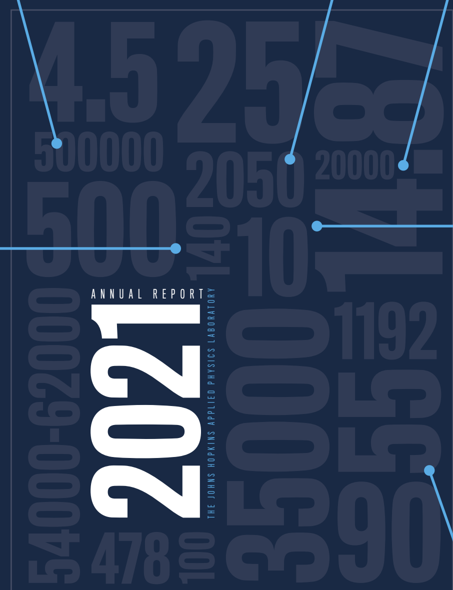
During a Navy assessment, MOSAICS monitored a 3,000-node network and successfully identified every adversarial attack, achieving a 100% success rate with fewer than 1% false positives.

READ MORE ON PAGE 9.

## 25%

APL's newest biosafety lab will bolster the research done in the Lab's other biosafety laboratories, increasing the nation's capacity for study in this field by 25%.

READ MORE ON PAGE 46.




## 35,000 kids STEM

APL STEM Program Manager Dwight Carr says that without his talented team, "there's no way we could have worked with over 35,000 kids, awarded over $200,000 in scholarships and reached over 800 teachers."

READ MORE ON PAGE 61.

## 2050 and beyond

APL hosted a workshop that explored the future of autonomous systems and their ability to change concepts of operation into 2050 and beyond.

READ MORE ON PAGE 19.

## 14.87 solar radii

At 14.87 solar radii (about 6.47 million miles) from the Sun's surface, Parker Solar Probe passed through a coronal pseudostreamer — a bright, loop-like structure that ascends high above from the Sun's surface.

READ MORE ON PAGE 23.

## 20,000 simulations

APL conducted nearly 20,000 simulations of DART's final four hours, accounting for a wide range of possible asteroid shapes and light-refraction scenarios.

READ MORE ON PAGE 9.

## 10 best places to work

For the fourth year in a row, APL made the Insider Pro and Computerworld "Best Places to Work in IT" list, moving up to No. 10 in the rankings.

READ MORE ON PAGE 66.

## 1,182 patients

APL sorted data collected from 1,182 COVID-19 patients and used an algorithm to predict the patients' likely disease course two weeks after hospital admittance.

READ MORE ON PAGE 32.

## 55 experts on staff

The 11-week Demonstration and Shakedown Operation (DASO-31) on a nuclear ballistic missile submarine required the expertise of 55 APL staff members.

READ MORE ON PAGE 16.

## 90% of Europa's surface

APL leads the development of the Europa Imaging System instrument, which will capture high-resolution images and map about 90% of the moon's surface at 330 feet per pixel.

READ MORE ON PAGE 29.

## 350 staff members

More than 350 APL staff members taught courses within the Johns Hopkins Engineering for Professionals (EP) program.

READ MORE ON PAGE 56.

## 10 times the strength

APL developed a chemical catalyst and crosslinker that accelerate the cure rate of underwater adhesives. After 24 hours, the glue will hold at 10 times the strength.

READ MORE ON PAGE 26.

## 100 inventions

Climate TRACE, a tool to measure human-caused greenhouse gas emissions, was honored as one of the top 100 inventions of 2020 by Time magazine.

READ MORE ON PAGE 37.

## 43000 square feet

With the opening of the three new buildings, the Lab has an additional 43,000 square feet of secure space.

READ MORE ON PAGE 46.

## 500 miles

A couple of minutes before collision, DART will coast for more than 500 miles at about 4 miles per second (or 14,400 miles per hour) until impact.

READ MORE ON PAGE 7.

## 400,000 per hour

The Parker Solar Probe heat shield ceramic coating can attach to a carbon substrate without chemically reacting and maintain its structural integrity and volume while cruising through hot plasma at more than 400,000 miles per hour.

READ MORE ON PAGE 25.

## 90,000 square feet

APL's Building 201 contains 90,000 square feet of lab space dedicated to microelectronics, imaging, additive manufacturing, chemistry, biology, quantum computing and other disciplines.

READ MORE ON PAGE 44.

## 2 million degrees

At close to 2 million degrees Fahrenheit, the solar atmosphere, or corona, is a brutal environment for a spacecraft to endure, but with Parker Solar Probe, APL's engineers made it happen.

READ MORE ON PAGE 21.


## 9,000 square feet

The Central Spark facility almost tripled its footprint with a move to a fully renovated 9,000-square-foot space, and it remains open around the clock to all staff members who wish to take advantage of the innovation center's sophisticated virtual reality, augmented reality, 3D printing and other capabilities.

READ MORE ON PAGE 65.

## -180 degree chamber

APL's temperature altitude chamber is the only one in the U.S. capable of reaching −180 degrees Celsius at simulated altitudes.

READ MORE ON PAGE 47.

## 119 subcontracts

In 2021, APL had 119 subcontracts to 48 different universities

READ MORE ON PAGE 72.

## 4 hours

SMART Nav will enable DART to conduct the last four hours of the mission without human intervention.

READ MORE ON PAGE 7.

## 263,000 square feet

Increasing the scope of APL's recent open-concept collaboration and work spaces, Building 201 boasts 263,000 square feet of complex, reconfigurable labs and flexible office space housed around a core four-story atrium.

READ MORE ON PAGE 44.

## 5th mission

As the fifth mission in NASA's Solar Terrestrial Probes program, IMAP will deepen our understanding of the boundary of the heliosphere, the protective bubble surrounding the solar system created by the Sun's solar wind and magnetic field.

READ MORE ON PAGE 29.

## 1,800 degrees

The leading edges of hypersonic vehicles must be protected against speeds exceeding Mach 5, which lead to temperatures well above 1,800 degrees Fahrenheit.

READ MORE ON PAGE 24.

## 79 years

For 79 years, APL has developed and served as a technical resource for many of the technologies that have proven crucial for the defense of the nation.

READ MORE ON PAGE 12.