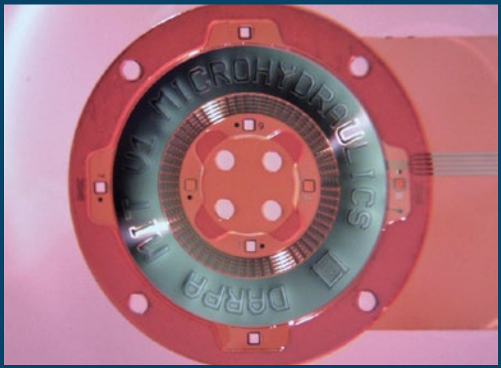
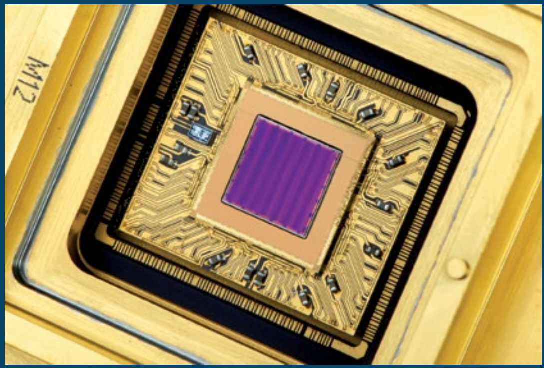
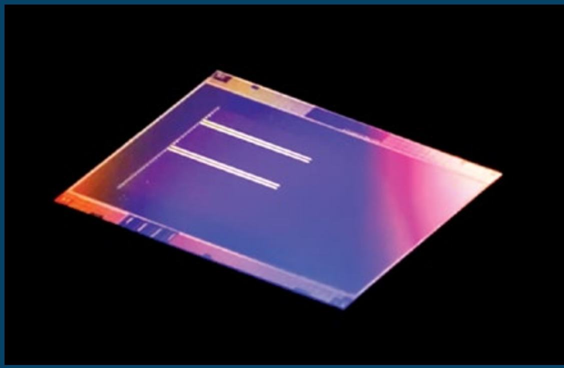
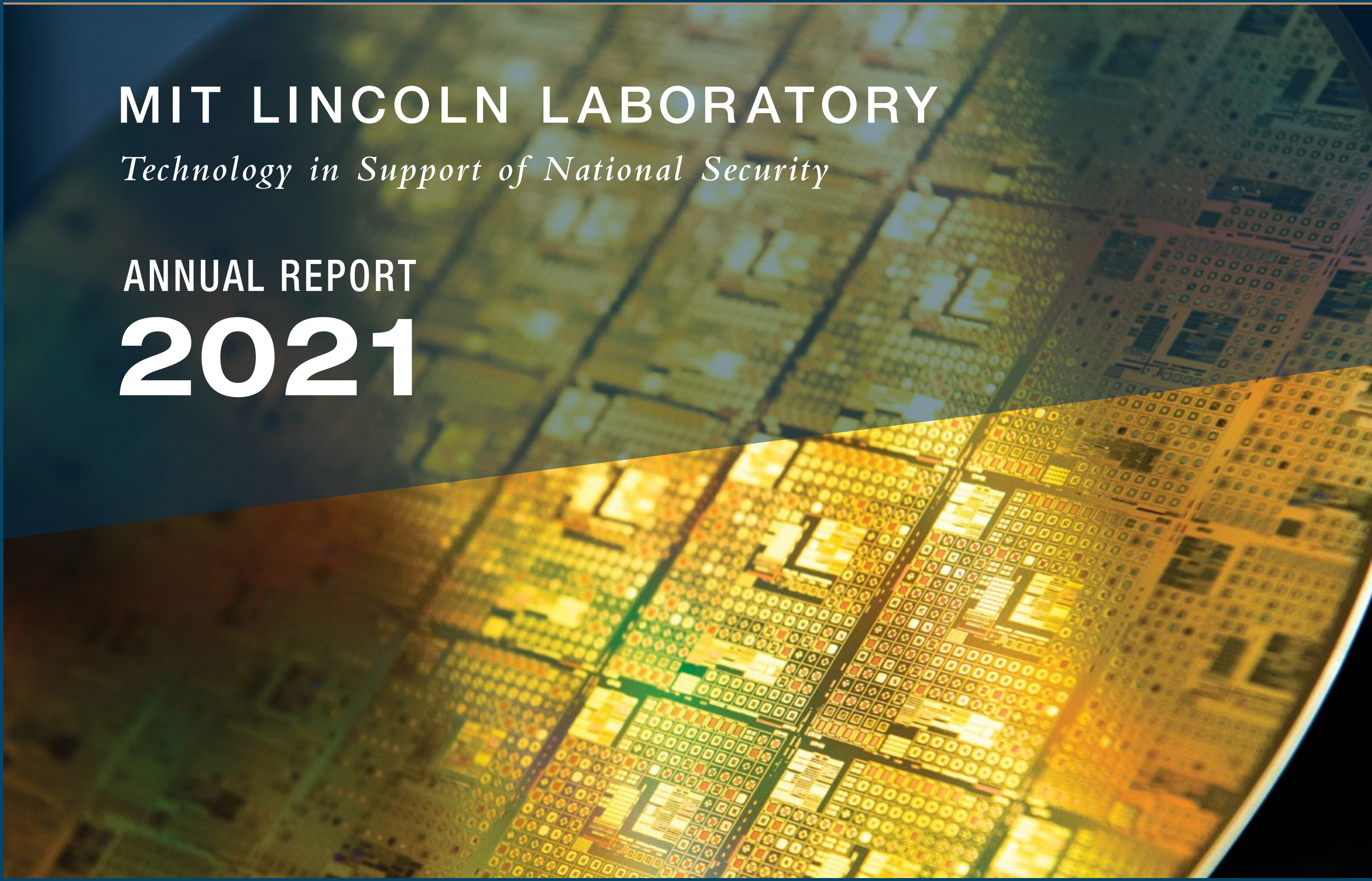


MIT LINCOLN LABORATORY

Technology in Support of National Security

ANNUAL REPORT 2021



Massachusetts Institute of Technology

Lincoln Space Surveillance Complex, Westford, Massachusetts

MIT Lincoln Laboratory

Reagan Test Site, Kwajalein Atoll, Marshall Islands

MIT LINCOLN LABORATORY 2021

MISSION

Technology in Support of National Security

MIT Lincoln Laboratory employs some of the nation's best technical talent to support system and technology development for national security needs. Principal core competencies are sensors, information extraction (signal processing and embedded computing), communications, integrated sensing, and decision support. Nearly all of the Lincoln Laboratory efforts are housed at its campus on Hanscom Air Force Base in Massachusetts.

MIT Lincoln Laboratory is designated a Department of Defense (DoD) Federally Funded Research and Development Center (FFRDC) and a DoD R&D Laboratory. The Laboratory conducts research and development pertinent to national security on behalf of the military Services, the Office of the Secretary of Defense, the Intelligence Community, and other government agencies. Lincoln Laboratory focuses on the development and prototyping of new technologies and capabilities to meet government needs that cannot be met as effectively by the government's existing in-house or contractor resources. An emphasis is on R&D to address emerging DoD technology areas. Program activities extend from fundamental investigations through design and field testing of prototype systems using new technologies. A strong emphasis is placed on the transition of systems and technology to the private sector. Lincoln Laboratory has been in existence for 70 years. On its 25th and 50th anniversaries, the Laboratory received the Secretary of Defense Medal for Outstanding Public Service in recognition of its distinguished technical innovation and scientific discoveries.

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Letter from the Director

In 2021, Lincoln Laboratory marked its 70th anniversary of developing advanced technology for national security. From the Laboratory's early focus on a radar-based national air defense system to the current work in areas ranging from cybersecurity to biomedical applications, our talented staff have brought much technical depth and field-testing experience to bear on difficult problems. Throughout the COVID-19 pandemic, we sustained our R&D through creative, diligent efforts to make remote and hybrid work productive.

The Laboratory continues to evolve. This year, we established a Laboratory Digital Engineering Center to incorporate new digital engineering approaches into building advanced prototypes. The focus is on developing an integrated process that includes the digital modeling/simulation and data processing required to realize modern hardware and software systems.

Artificial intelligence (AI) continues to be a significant enabling technology in all our mission areas. We are exploring the potential for AI to enhance the decision support capabilities provided by the various systems we develop. This year, our centralized AI Technology Group conducted research to enhance the trustworthiness and mission-readiness of AI systems.

After several years of Laboratory development, a 3U small satellite (CubeSat) was launched by NASA to serve as a pathfinder for the constellation of these CubeSats designed for the NASA TROPICS (Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats) program. When TROPICS is fully implemented, six CubeSats, traveling in three low-Earth orbits over the global tropical belt, will deliver vital measurements of a storm every 45 minutes. This rapid revisit rate and the CubeSats' sensitive instrumentation will enable researchers to expand monitoring and study of the evolution of severe storms.

Our R&D realized several milestones in mission areas across the Laboratory:

- We transitioned a prototype extremely wide field-of-view imaging sensor to the U.S. Army Combat Capabilities Development Command Aviation and Missile Center for further testing as a government reference sensor. This resource for future space sensor programs won the Missile Defense Agency's Innovation Team Award.
- To advance research into quantum information sciences, we developed a trapped-ion system that achieved the first demonstration of integrating laser signals into a substrate that contains the ion-trap electrodes.
- We successfully conducted airborne demonstrations of scalable, resilient, line-of-sight communication networking techniques that enable Department of Defense platforms to reliably connect and share data.
- In collaboration with physicians at Mass General Brigham, we prototyped and tested a device that uses AI and handheld robotics to allow first responders to perform emergency vascular access on a patient at the scene of an injury.
- In our continued work to develop a cyber-resilient operating system layer, we demonstrated an application to enable software-based high-assurance cryptography in platforms highly constrained by size, weight, and power needs.
- The bidirectional space-to-ground laser communication system we built features a highly integrated mechanical and electrical design to provide a 10-megabits-per-second downlink from geosynchronous orbit and a 2-kilobits-per-second uplink from the ground.
- Under sponsorship of the Federal Aviation Administration, we are developing algorithms that allow small unmanned aircraft systems (sUAS) to detect and avoid other aircraft, a key capability enabling commercial sUAS operations.
- Nine technologies developed at Lincoln Laboratory won 2021 R&D 100 Awards; since 2010, the Laboratory has earned 75 of these awards recognizing technical innovation.

Many examples of our technical milestones, efforts to support an inclusive workplace, and educational and community outreach activities are described in this report. Our accomplishments continue to be enabled by our strong commitment to technical excellence, integrity, and service to the nation.

Sincerely,

Eric D. Evans
Director

MIT Lincoln Laboratory

MISSION: TECHNOLOGY IN SUPPORT OF NATIONAL SECURITY

VISION

To be the nation's premier laboratory that develops advanced technology and system prototypes for national security problems

- To work in the most relevant and difficult technical areas
- To strive for highly effective program execution in all phases

VALUES

- **Technical Excellence:** The Laboratory is committed to technical excellence through the people it hires and through its system and technology development, prototyping, and transition.
- **Integrity:** The Laboratory strives to develop and present correct and complete technical results and recommendations, without real or perceived conflicts of interest.
- **Meritocracy:** The Laboratory bases career advancement on an individual's ability and achievements. A diverse and inclusive culture is critically important for a well-functioning meritocracy.
- **Service:** The Laboratory is committed to service to the nation, to the local community, and to its employees.

STRATEGIC DIRECTIONS

- Continue evolving mission areas and programs
- Strengthen core technology programs
- Increase MIT campus/Lincoln Laboratory collaboration
- Strengthen technology transfer to acquisition, user, and commercial communities
- Find greater efficiencies and reduce overhead process
- Improve leverage through external relationships
- Improve Laboratory diversity and inclusion
- Enhance Laboratory facilities
- Enhance Laboratory community outreach and education

MIT and Lincoln Laboratory Leadership

Massachusetts Institute of Technology

Dr. L. Rafael Reif
President

Dr. Martin A. Schmidt (left)
Provost

Dr. Maria T. Zuber (right)
Vice President for Research

MIT Lincoln Laboratory

(Left to right)

Chevalier P. Cleaves
Chief Diversity & Inclusion Officer

Dr. Eric D. Evans
Director

Robert A. Bond
Chief Technology Officer

Dr. Melissa G. Choi
Assistant Director

Dr. Bernadette Johnson
Chief Technology Ventures Officer

Dr. Justin J. Brooke
Assistant Director

Dr. Israel Soibelman
Chief Strategy Officer

C. Scott Anderson
Assistant Director – Operations

ORGANIZATIONAL CHANGES

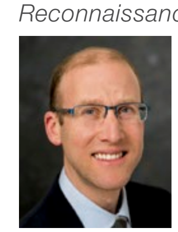
Heidi C. Perry
Chief Technology Officer

As Chief Technology Officer, Ms. Perry will contribute to the office's development of the Laboratory's long-term technology strategy and the coordination of collaborative research with MIT campus. Ms. Perry was an Assistant Head of the Air, Missile, and Maritime Defense Technology Division prior to her appointment to the Technology Office. She served as the division's Chief Innovation Officer and played an important role in enhancing the Laboratory's naval systems and technology programs. She worked closely with the Technology Office on autonomy and artificial intelligence initiatives and was a division liaison to the Technology Ventures Office.

Jaymie A. Durnan
Assistant to the Director for Strategic Initiatives

Mr. Durnan has demonstrated significant expertise in leadership and management, strategy development and execution, policy development, programming and budgeting, and systems acquisition. His private sector experience includes service as a Senior Vice President and Special Counsel to the chairman of MacAndrews & Forbes Holding, Inc., and the Managing Member of a strategic advisory firm. His government service includes being an assignee to the staff of the Chairman of the Joint Chiefs of Staff, supporting arms control negotiations, and a military social aide to the President of the United States.

Daniel J. Ripin
Assistant Head, Intelligence, Surveillance, and Reconnaissance and Tactical Systems Division



Dr. Ripin has extensive experience directing major R&D efforts in vital national security areas, such as high-energy laser systems and advanced imager technology. As program manager of Lincoln Laboratory's first Level-1 program, he demonstrated the ability to build and lead high-performing, highly collaborative teams. Recently, he served as co-lead of Lincoln Laboratory's Long-Term Planning Panel for the COVID-19 Task Force and has been involved in promoting diversity and inclusion within the Laboratory community.

Gregory D. Berthiaume
Assistant Head, Space Systems and Technology Division

Dr. Berthiaume held several leadership positions in the Sensor Technology and System Applications Group prior to his division-level appointment. He is recognized as a leader in the science community for his contributions to microwave sounder algorithm development, grew the Laboratory's NASA/National Oceanic and Atmospheric Administration portfolio, and held a two-year joint appointment with the MIT Kavli Institute for Astrophysics and Space Research, which led NASA's Transiting Exoplanet Survey Satellite program. In 2019, he was awarded the NASA Exceptional Public Service Medal for his contributions to NASA space and earth science missions.

James A. Kennedy
Chief Security Officer and Head, Security Services Department

Mr. Kennedy has 37 years of experience in Department of Defense and Intelligence Community industrial security programs. He most recently served as Security Director for Lockheed Martin Military Space and Commercial Civil Space in Sunnyvale, California. His past security leadership roles include Security Director for General Dynamics Mission Systems and Harris Corporation, and Senior Corporate Director for Telecommunications Systems, Inc.

Derek W. Jones
Deputy Chief Security Officer

Since joining the Security Services Department in 2003, Mr. Jones has held positions in several areas, including personnel security, business operations, and industrial security. In 2019, he was appointed Assistant Department Head, with responsibility for overseeing the management of industrial security and special programs for Lincoln Laboratory's main complex and its remote field sites. Currently, he is a member of the National Industrial Security Program Policy Advisory Committee (NISPPAC), serving as chair of the NISPPAC Policy Working Group and co-chair of the Federally Funded Research and Development Center/University Affiliated Research Center Policy Working and Operations.

>> *Continues on page 6*

Jacob M. Williams

Head, Program Management Office

Dr. Williams joined Lincoln Laboratory in March 2021. He previously served as L3Harris's Director of Programs for the Integrated Vision Solutions Sector, where he led programs in advanced night-vision devices for the U.S. Army. During his career, he has been deeply involved in the development and management of systems related to space and missile defense technology. In 2015, while at L3 Technologies Cincinnati Electronics (now L3Harris), he led the development, qualification, and production of the common avionics for the Atlas and Delta launch vehicles and directed multiple improvement efforts in the Space Avionics Division.

Christiaan M. Stone

Deputy Director, Policy, Compliance, Labor and Employee Relations, Human Resources

In 2008, Mr. Stone joined MIT as the Assistant Manager of Labor Relations. He joined the Laboratory in 2014, most recently as the Manager of Labor and Employee Relations. He and his team oversee all labor relations with the unionized staff at the Laboratory as well as employee relations for Lincoln Laboratory employees.

Kenneth Sims

Assistant Head, Business Transformation Office

Mr. Sims began his career at Lincoln Laboratory as a business manager in the Security Services Department in 2012 and moved on to serve in business manager roles in two technical divisions. He has overseen all operations for procurement, facilities, human resources, and financial matters for the Advanced Technology Division and took a lead in growing the off-contract portfolio across the division. Recently, he served as the program manager for the S/4 HANA Financial Modernization effort that is part of the Laboratory's overall Digital Enterprise Transformation.

Diane J. Shea

Assistant Department Head, Contracting Services Department

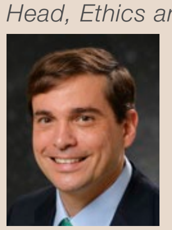
Ms. Shea joined MIT as the Associate Director of Procurement in 1995 and ultimately served as the Director of Procurement. She joined the Laboratory in 2010; her most recent role was as Senior Manager of Procurement. She and her team manage all aspects of operational contracting. In the Assistant Department Head position, she will be focused on acquisition.

Establishment of the Ethics and Compliance Assurance Office

This new office centralizes the activities involved in maintaining Lincoln Laboratory's high ethical standards and in assuring compliance with contractual and government regulations. The Ethics and Compliance Assurance Office (ECAO) within the Director's Office provides comprehensive, current information on ethics and compliance matters. The ECAO closely collaborates with the Security Services, Human Resources, and Contracting Services Departments, as well as with the MIT Office of General Counsel. The office also serves as the primary Lincoln Laboratory interface with the MIT Audit Division.

David Suski

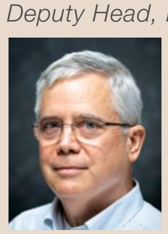
Head, Ethics and Compliance Assurance Office



Mr. Suski, who continues to be a member of the MIT Office of the General Counsel, leads the new ECAO's efforts to advise on contractual issues arising out of Lincoln Laboratory's national defense research and to maintain the Laboratory's robust ethics program. He has significant expertise in national security law, government contracts, litigation, administrative law, government ethics, and congressional affairs. Before joining MIT, he served as Assistant General Counsel with the Central Intelligence Agency, where he served assignments at the Counterterrorist Center, the Office of Congressional Affairs, and the Special Activities Division.

Peter H. Babcock

Deputy Head, Ethics and Compliance Assurance Office



Continuing his role as the Assistant Ethics Officer at Lincoln Laboratory while serving as Deputy Head of the ECAO, Mr. Babcock leads a team that has oversight of conflict-of-interest situations, reviews whistleblower complaints, and maintains the Laboratory's Ethics Hotline. Prior to joining the Laboratory, he worked as a civilian attorney for the U.S. government for more than 30 years. He also served as a Reserve Officer in the U.S. Air Force Judge Advocate's Corps, attaining the rank of lieutenant colonel.

William P. Surrey

Assistant Department Head, Contracting Services Department

Most recently, Mr. Surrey was the Director of Contracting for the Rapid Capabilities Office of the U.S. Space Force. He is a retired colonel and a project management professional. He also served as the Deputy Director of Contracting at the Air Force Life Cycle Management Center, Hanscom Air Force Base, in 2017 and 2018. Mr. Surrey's focus in this position will be logistics, compliance, and contracts.

Todd R. Lardy

Chief Test Pilot, Flight Test Facility

Prior to joining the Laboratory, Mr. Lardy was an engineering flight test pilot at Cessna Aircraft Company, where he was responsible for conducting developmental flight tests on the Citation XLS, Bravo, Encore, and CJ2. He joined Lincoln Laboratory in 2006 as a research test pilot at the Flight Test Facility. Since being hired, he has flown the first flights on modifications to the Laboratory's Twin Otter, Falcon 20, and Gulfstream test aircraft and is the lead airworthiness test pilot. He is type rated in five aircraft, has nearly 6,000 flight hours in 50 aircraft, and is an Associate Fellow in the Society of Experimental Test Pilots.

Christa N. Frey

Supervisor of Flight Test Operations, Flight Test Facility

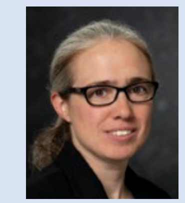
Ms. Frey joined the Laboratory in January 2010 as a research test pilot at the Flight Test Facility. Her career spans more than 25 years in aviation and flight testing. She has flown over 5,000 flight hours in more than 25 different aircraft, including nearly 2,000 hours in experimental, highly modified aircraft. She has attended numerous short courses at the National Test Pilot School, Naval Test Pilot School, and Air Force Safety Center. She is a certified flight instructor and a certified public accountant and project management professional. In addition to her work at the Laboratory, Ms. Frey is also a lieutenant colonel in the Air National Guard, where she currently flies the KC-46 Pegasus aircraft.

Establishment of the Digital Engineering Center

The new Digital Engineering Center will coordinate the development and adoption of modern digital engineering practices that enhance Laboratory prototyping capabilities, conduct novel research in digital engineering, and act as a resource for the Department of Defense (DoD) and the broader Laboratory sponsor community. Key technical emphases will include the further adoption and integration of model-based practices into end-to-end prototyping workflows, and the leveraging of shared data, models, enhanced simulation, and advancements from relevant fields, such as high-performance computing and artificial intelligence.

Denise A. Fitzgerald

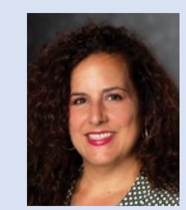
Leader, Digital Engineering Center



Ms. Fitzgerald served as Assistant Group Leader in the Mechanical Engineering Group, where she managed the designer cell, spearheaded the transition to SolidWorks 3D computer-aided design, and led the selection and implementation of the product lifecycle management tool Aras Innovator. Recently, she has coordinated with external agencies to influence DoD platform implementation.

Stephanie H. Sposato

Associate Leader, Digital Engineering Center



Dr. Sposato led several data collection and analysis programs prior to her promotion to her previous role as Assistant Leader of the Fabrication Engineering Group. She served as the deputy program manager of the countermeasure programs and has been responsible for redefining fabrication processes to fully leverage available digital technology.

TECHNOLOGY INNOVATION 9

The Laboratory's field-programmable imaging array (FPIA) chip has more than 6.6 billion transistors. An architectural innovation, the FPIA serves as a universal digital back end for optical detectors.

The six TROPICS satellites pictured here will be launched in 2022. Lincoln Laboratory led the program's development, and designed and built the microwave radiometer (the gold-foiled cube) at the top of each satellite. Image: Blue Canyon Technologies

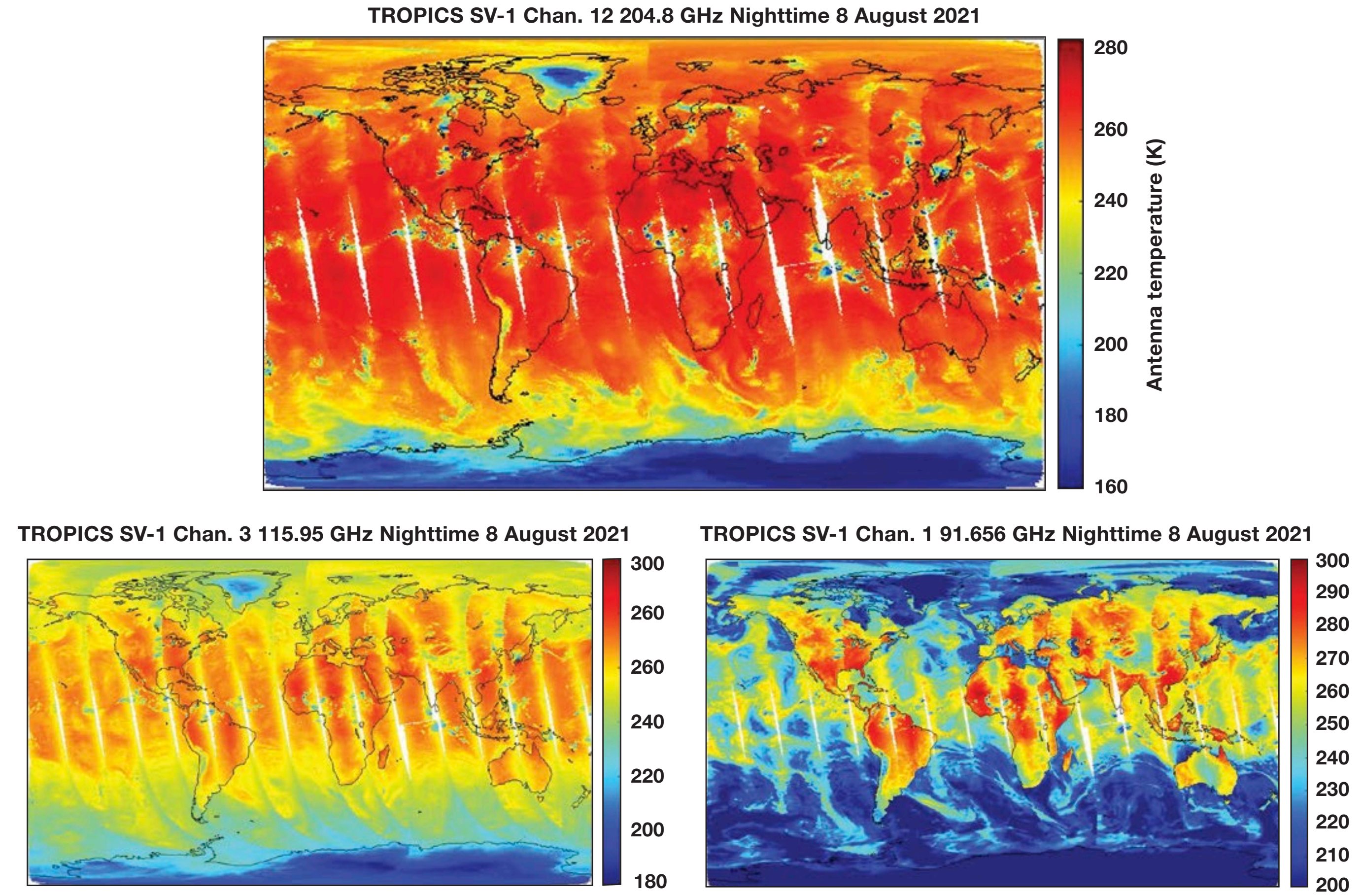
Tiny Satellites Will Study Big Storms

In 2021, Hurricane Ida struck Louisiana as a powerful Category 4 hurricane, bringing destructive storm surge, winds, and rainfall. An alarming feature of Hurricane Ida was how quickly the storm intensified. Scientists warn that such intensification is becoming more common with climate change, but the exact conditions that fuel this rapid growth are not yet well understood.

The TROPICS (Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats) mission will increase the amount of data collected about tropical storms, enabling a deeper analysis of their evolution. Six small satellites, each about the size of a half-gallon milk carton, will be spread out in three low-Earth orbits to watch over the globe's tropical band where these storms form. A satellite in the constellation will revisit a storm roughly every 45 minutes, a much higher rate than is possible today, and collect updated temperature, water vapor, precipitation, and cloud ice measurements.

Lincoln Laboratory proposed this first-of-its-kind mission to NASA as part of the Earth Venture Instrument competition. In 2021, NASA launched a test satellite, called the TROPICS Pathfinder. The six constellation satellites will follow in 2022.

The TROPICS satellites collect data by microwave radiometer. On current weather satellites, these instruments are the size of a washing machine. On TROPICS, they are the size of a coffee cup. Researchers at the Laboratory and the University of Massachusetts Amherst worked together over the last decade to achieve this miniaturization with little compromise in performance, with the goal of putting the instruments on small, inexpensive satellites for targeted weather observations.

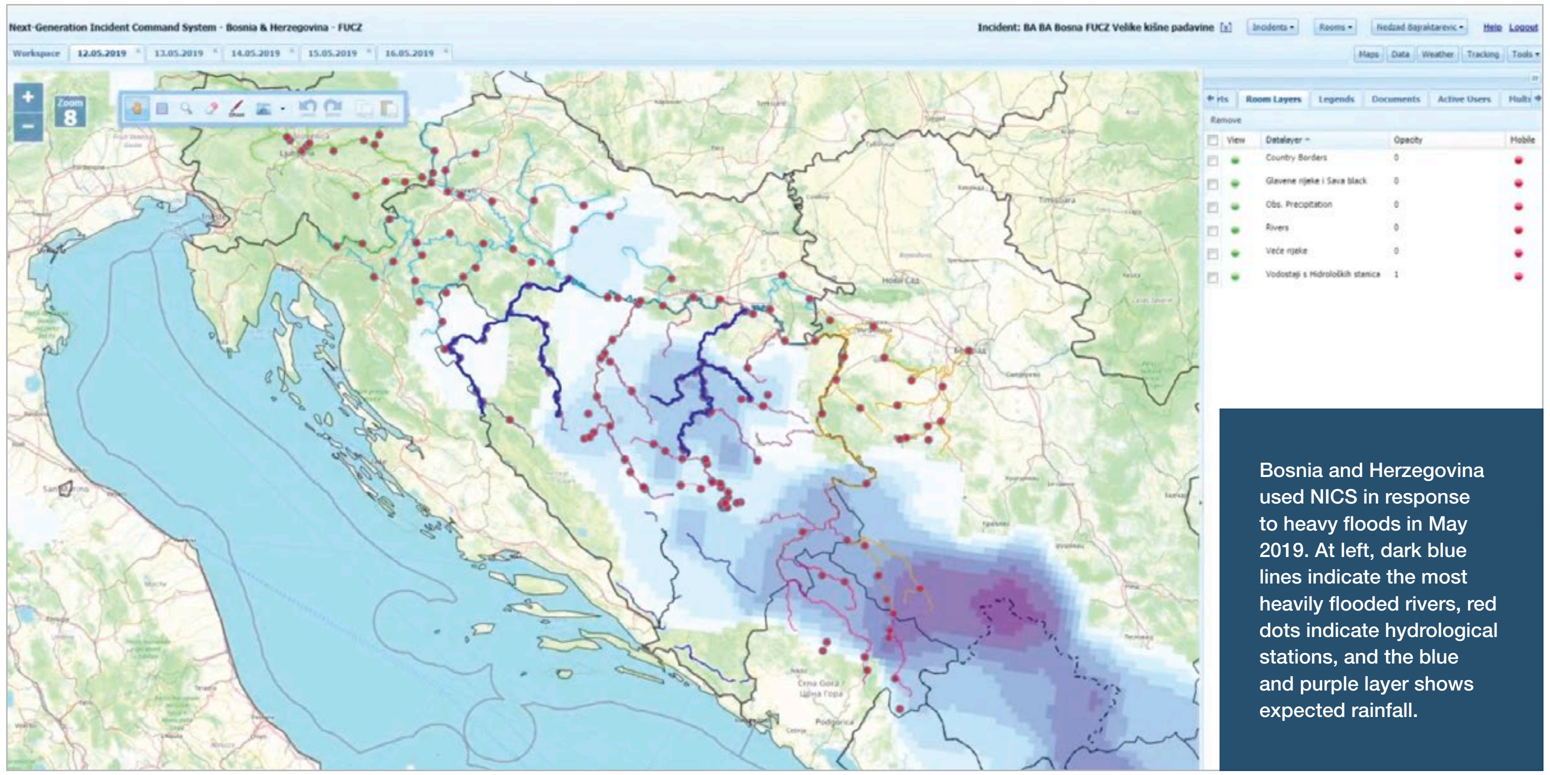


On August 8, 2021, the TROPICS Pathfinder satellite captured its first global data, including a channel around 205 gigahertz (top), which is a completely new imaging channel for space-borne microwave radiometers.

The TROPICS Pathfinder satellite pictured here entered orbit in June 2021 and successfully tested the technology, communication systems, data processing, and data flow in advance of the constellation's full launch. Image: Blue Canyon Technologies

Microwave radiometers work by detecting the thermal radiation emitted by oxygen and water vapor in the air. The TROPICS instrument measures these emissions at different heights throughout the atmosphere, corresponding to 12 RF channels between 90 gigahertz and 205 gigahertz. The 205-gigahertz channel is the highest frequency ever used on a space-borne microwave cross-track-scanning radiometer. It holds promise for scientists to learn more about mechanisms in the cloud formation process. For example, they can more closely observe the transition of liquid cloud droplets to ice cloud crystals, which are an important component in cloud formation processes and are not observed with sufficient fidelity by current microwave, infrared, or visible systems.

Soon after producing its first-light images in August, the TROPICS Pathfinder provided insight into the structure of Hurricane Ida before and after its landfall. In 2022, the full constellation will enable even more frequent data collections and clues into how atmospheric conditions impact tropical storm intensity. The TROPICS team—which spans the Laboratory, NASA, National Oceanic and Atmospheric Administration, and several universities—expects that these observations will also improve forecasts, helping people get to safety sooner and protect critical infrastructure.

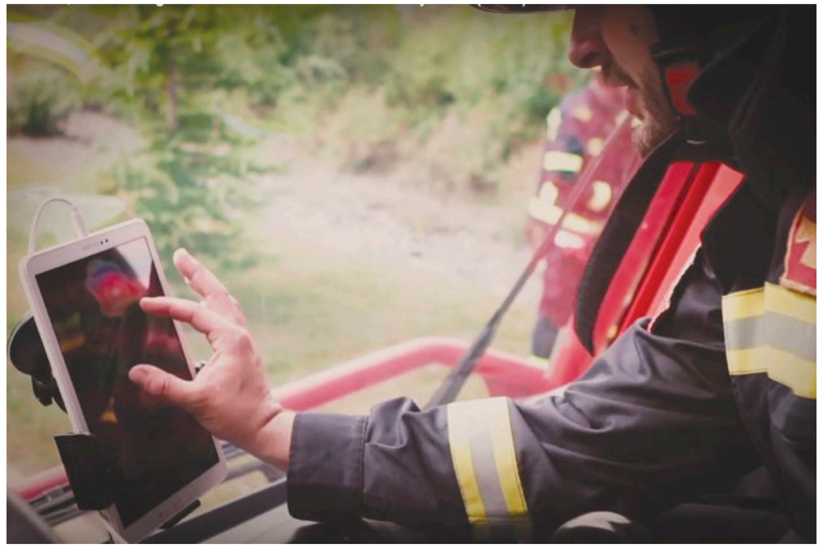


Bosnia and Herzegovina used NICS in response to heavy floods in May 2019. At left, dark blue lines indicate the most heavily flooded rivers, red dots indicate hydrological stations, and the blue and purple layer shows expected rainfall.

Disaster Management System Takes Root in the Western Balkans

After a five-year partnership between Lincoln Laboratory, the NATO Science for Peace and Security Programme, and the Department of Homeland Security Science and Technology Directorate, national emergency agencies in the Western Balkans are now fully equipped with the Next-Generation Incident Command System (NICS). The system, developed at the Laboratory, is helping the region coordinate its response to disasters in and across Croatia; Bosnia and Herzegovina; North Macedonia; and Montenegro.

Natural disasters frequently impact this part of the world. After devastating floods swept across the Balkans in 2014, NATO sought to improve crisis management in the region. At that time, the Laboratory had already developed NICS to improve the coordination of wildfire response in California. After learning about NICS at a conference, NATO officials initiated the Advanced Regional Civil Emergency Coordination Project to extend the technology to those Balkan countries that had expressed interest in the project.



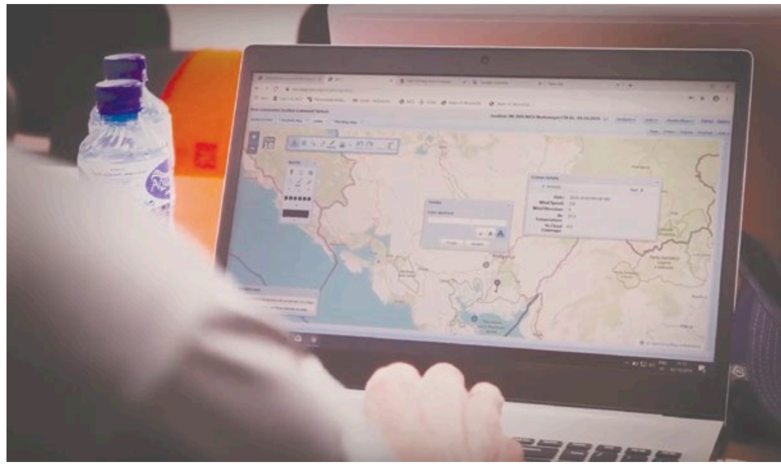
First responders access a mobile version of NICS while participating in a large-scale disaster response exercise hosted by the NATO Euro-Atlantic Disaster Response Coordination Centre. Image: NATO

NICS is a web-based software platform and mobile app that allows first responders to efficiently share information about a disaster in a unified digital space. A team of Laboratory developers worked closely with local and federal agencies in each of the countries to understand how best to adapt NICS to serve their needs and to train personnel to use it.

At the center of NICS is an interactive incident map. On the map, responders can draw incident perimeters, designate evacuation zones, track their locations in real time, and share geotagged images or videos from the scene. Each incident map is associated with a collaboration room, through which responders and commanders can communicate. Because NICS was initially developed for wildfires, a key upgrade was making NICS flexible and user friendly for different, and simultaneous, types of responses, such as water rescues, urban searches, and chemical emergencies. To support this need, the incident map was adapted to filter data by response type and expanded to support tailored tracking of resources. These changes have allowed multiple emergency entities to both gain visibility into the entire incident and focus on their own area of interest.

Throughout this project, the NATO Euro-Atlantic Disaster Response Coordination Centre has held annual, large-scale disaster response exercises that have served as milestones for testing the technology. This year's exercise, which was held in North Macedonia, marked the end of the Laboratory's role in this program and the formal transition of NICS to the partner countries.

The process of transitioning NICS as an operational platform has been unique to each country. Bosnia and Herzegovina, eager to adopt the technology at the national level, has used it in more than four dozen emergency incidents. The Red Cross in North Macedonia recognized a need for NICS in the early days of the COVID-19 pandemic, and the country has since been using it to coordinate resources and communicate directly to the public about clinic locations and case numbers. A strong earthquake in Croatia at the end of 2020 mobilized their first real-world use of the system.



An emergency commander monitors and posts updates to the NICS incident map. The map can show incident locations, evacuation zones, videos from a scene, and other data to provide situational awareness to first responders. Image: NATO

Today, Laboratory researchers are investigating other uses for NICS on sponsored programs. The developers are also hoping to engage organizations to build an active open-source community around the software. Such a community can help evolve and support the software for continued worldwide adoption.

Laboratory researcher Stephanie Foster, pictured second from right, led the NICS NATO program. Joining Foster in the photo are directors of emergency management agencies from the participating countries and NATO Science for Peace and Security Programme members.

Don Bansleben, S&T Program Manager, uses a small sprayer to release a plume of sugar-based particles into the air in Union Square in Manhattan. The particles contain unique DNA sequences that allow researchers to track their dispersion when they are later collected and analyzed.

In New York City's Subway and Streets, Study Aims to Mitigate Chemical and Biological Airborne Threats

When the air harbors harmful matter, such as a virus or toxic chemical, it's not always easy to promptly detect this danger. Whether spread maliciously or accidentally, how fast and how far could hazardous plumes travel through a city? What could emergency managers do in response?

These were questions that scientists, public health officials, and government agencies probed with an air flow study conducted in October 2021. At 120 locations across New York City, a team led by Lincoln Laboratory collected safe test particles and gases released earlier in the subway and on streets. The exercise measured how far the materials had traveled and what their concentrations were when detected.

The results are expected to improve air dispersion models and, in turn, help emergency management planners improve response protocols if a real chemical or biological event were to take place.

The results are expected to improve air dispersion models and, in turn, help emergency management planners improve response protocols if a real chemical or biological event were to take place.

Above, at one of 120 sites in New York City, Laboratory researcher Christian Vanderloo collects filters containing samples of airborne particles. Below, Laboratory engineers designed this filter head to rotate through eight filters, eliminating time spent revisiting collection sites to replace used filters. A vacuum sucks air through each filter, trapping particles for analysis.

The study was performed under the Department of Homeland Security Science and Technology Directorate's (DHS S&T) Urban Threat Dispersion Project. This exercise followed a similar, smaller study in 2016 that focused mainly on the subway system within Manhattan.

The particles and gases used in the study are safe to disperse. The particulates are primarily composed of maltodextrin sugar and have been used in prior public safety exercises. To enable researchers to track the particles, the particles are modified with small amounts of synthetic DNA that act as a unique "barcode" corresponding to the location from which the particle is released and the day of release. The particles that get trapped in filters set up throughout the city are later analyzed.

Approximately 5,000 samples were collected over the five-day measurement campaign. The data are feeding into existing particle dispersion models to improve simulations. One of these models, from Argonne National Laboratory, focuses on subway environments, and another model from Los Alamos National Laboratory simulates above-ground city environments, taking into account buildings and urban canyon air flows. Together, these models can show how a plume would travel from the subway to the streets. These insights will enable emergency preparedness managers in New York City to develop more informed response strategies, as they did following the 2016 subway study.

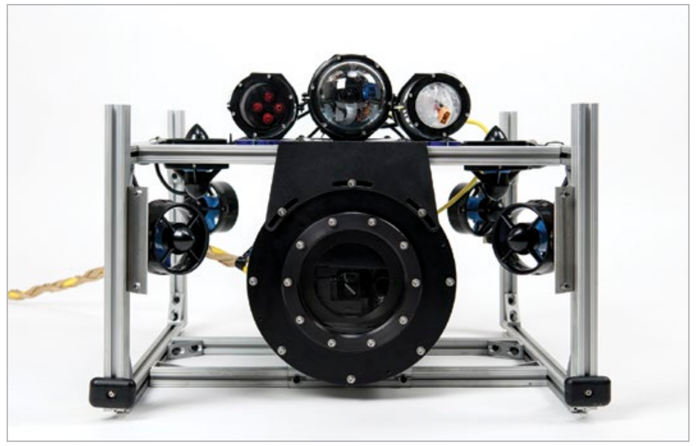
A team of nearly 175 personnel spanning the Metropolitan Transportation Authority, New York City Transit, New York City Police Department, Port Authority of New York and New Jersey, New Jersey Transit, New York City Department of Environmental Protection, New York City Department of Health and Mental Hygiene, National Guard Weapons of Mass Destruction Civil Support Teams, Environmental Protection Agency, and Department of Energy National Laboratories, in addition to S&T and Lincoln Laboratory, worked together on the exercise.

Now that researchers have learned more about how material transports through the subway system, a new program, called the Chemical and Biological Defense Testbed, is underway to investigate how to mitigate that transport in effective and safe ways. The goals of this test bed will be to develop architectures and technologies that could allow for a range of appropriate responses and to test the performance of new chemical and biological sensors.

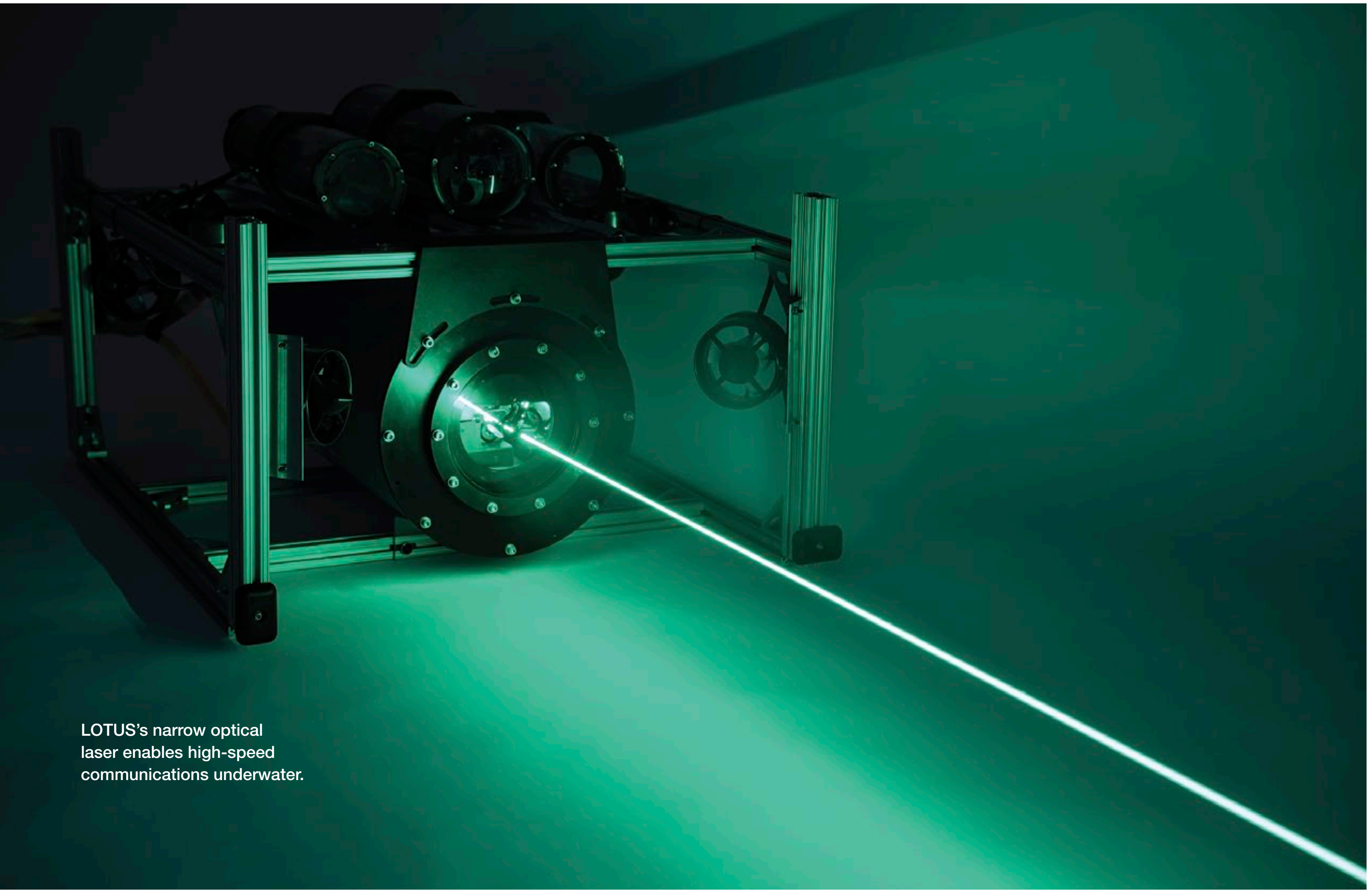
Optical Lasers Make High-Speed Links Underwater

For the past few decades, Lincoln Laboratory has been at the forefront of space communications. NASA's Lunar Laser Communication Demonstration (LLCD) is one example, in which researchers made history by using laser beams to transmit video data between a satellite orbiting the Moon and a ground station in New Mexico, at a rate six times faster than the current state of the art in RF communications systems.

The optical beam technology that led to the LLCD's success was developed at the Laboratory, and another team of researchers is now leveraging it for a new purpose in the LOTUS project. LOTUS stands for Lightweight Optical Telecommunication from Under Sea, and the program aims to deliver high-quality communications underwater.



LOTUS's laser communications terminal and beam director are shown in the above image (large cylinder at the bottom). The top middle cylinder is the remotely operated vehicle control capsule, and the thrusters are located on the vertical bars.



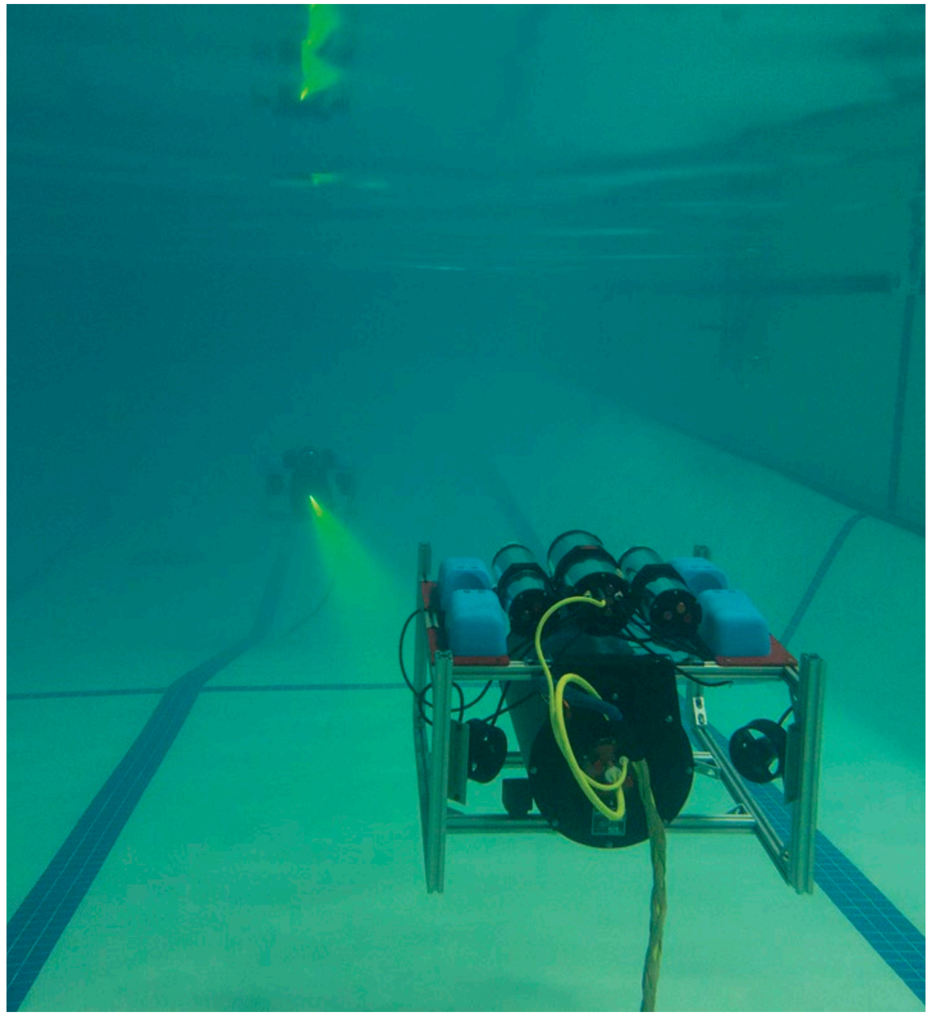
LOTUS's narrow optical laser enables high-speed communications underwater.

Fast and efficient underwater communications is a tricky challenge. The main reason relates to how water degrades and disrupts signals in a way that air does not. Sound and radio waves are the usual go-to signals in the underwater domain, yet they suffer from low data rates, short ranges, lack of precision, and inefficiency.

Optical lasers have potential for alleviating these issues because visible light operates at a frequency where attenuation in water is lowest. But the mechanics for making optical technology work have caused a roadblock. Currently, underwater platforms that use optics to communicate sweep a wide beam over a large area so that the receiver has a better chance of finding and catching the transmitter's signal. This strategy wastes a lot of energy and makes the system sensitive to background light. The receiver must have a wide lens to catch a wide beam, and too much extra light from the environment can blind the receiver and drown out the communications signal. As a result, these platforms can operate only at night.

The LOTUS platform is unique because it uses a very narrow laser beam, aided by complex, automated beam steering, to transmit data. With a narrow beam, the receiver can have a much narrower lens—similar to looking through a soda straw, the opening is small enough that only the beam comes through and background light cannot.

LOTUS's beam-steering mechanics came from the LLCD program—which required that team to send a beam to a receiver that was 239,000 miles away. For LOTUS, this precision is used to send the beam a much shorter distance but in a turbulent environment, where waves and currents cause the transmitter and receiver to be in motion. The capability to steer precisely enough to send and receive a narrow beam underwater is currently unique to Lincoln Laboratory.



In 2018, the team tested LOTUS in an indoor pool and sent communications between platforms that were separated by 20 meters. Given the results of their test, the team estimates they can link platforms that are up to 400 meters away in clear ocean water.

Compared to other underwater communications platforms, LOTUS can communicate more than 100,000 times faster and with 100 times less battery consumption. The need for less battery also translates to a smaller platform design. In addition, because the beam is narrow and emits less power, it poses no danger to humans or surrounding wildlife.

In 2021, the team continued to the test the system to prepare it for operational tasks. The LOTUS team sees this technology being adopted for many uses, such as for seafloor mapping and scientific missions, as well as for helping the military coordinate the routes of undersea vehicles.

Technology Investments

The Technology Office manages Lincoln Laboratory's strategic technology investments and helps to establish and grow technical relationships outside the Laboratory. The office is responsible for overseeing investments in both mission-critical technology and potentially impactful emerging technology. To maintain an awareness of emerging national security problems and applicable technologies, the office interacts regularly with the Office of the Under Secretary of Defense for Research and Engineering and other government agencies. The Technology Office fosters collaborations with and supports university researchers, and aids in the transfer of next-generation technology to the Laboratory's mission areas. The office also works to enhance inventiveness and innovation at the Laboratory through various investments and activities that promote a culture of creative problem solving and innovative thinking.

In 2021, pandemic-related work restrictions for Lincoln Laboratory and its campus collaborators presented challenges for applied research. However, the pandemic also created new opportunities for virtual interactions through the implementation of new digital tools. Given the new hybrid work environment, the ability to work remotely and with distant collaborators will only strengthen the Laboratory's research capabilities going into the new normal.

LEADERSHIP
Mr. Robert A. Bond, Chief Technology Officer (center)
Ms. Anu K. Myne, Associate Technology Officer (left)
Dr. Jesse A. Linnell, Associate Technology Officer (right)

INVESTMENTS IN MISSION-CRITICAL TECHNOLOGY

Enabling development of technologies that address long-term challenges and emerging issues within the Laboratory's core mission areas

Cybersecurity

All branches of the U.S. government, including the Department of Defense (DoD), must continuously defend against diverse and persistent cyberattacks. Lincoln Laboratory conducts research and develops technology to secure, defend, operate, and ensure the resiliency of the nation's cyber systems. Starting with detailed understanding and analysis of cybersecurity issues, the Laboratory executes advanced security research across the full spectrum of the cyber problem space, from secure software and hardware architectures to innovative algorithm development and vulnerability characterization. In 2021, Lincoln Laboratory continued fundamental research in cybersecurity through the exploration and development of cybersecurity phenomenology, resilient systems, data-centric architectures, and system exploitation. Examples of this R&D are listed below:

- Designed the Lincoln Exploitation Exploration Tool to greatly increase the speed of vulnerability discovery. The tool applies techniques that check the flow of user inputs to discover software exploits.
- Investigated the use of advanced cryptographic techniques for system exploitation and to address privacy concerns with machine learning algorithms that use sensitive data.
- Invented a novel defense approach suitable for use in industrial control systems that have strict real-time requirements to ensure physical safety.
- Created a system architecture to enhance detection and situational awareness of illicit cryptocurrency transactions.
- Developed hardware and software approaches that compartmentalize Linux into smaller modules, each of which has the lowest privilege needed for its functionality. These approaches are expected to minimize the impact of cyber vulnerabilities in mission systems.

TECHNOLOGY HIGHLIGHT

Resilient Computer in the News

Mission-critical DoD systems use off-the-shelf components in their computing infrastructure. Such components, however, have vulnerabilities that expose the system to cyberattacks. Cyber vulnerabilities arise from the legacy designs of modern computing components, which were designed before specific security needs were understood in the community. "Add-on" cyber protections integrated into these components can only provide partial protection and can often be bypassed by well-resourced adversaries.

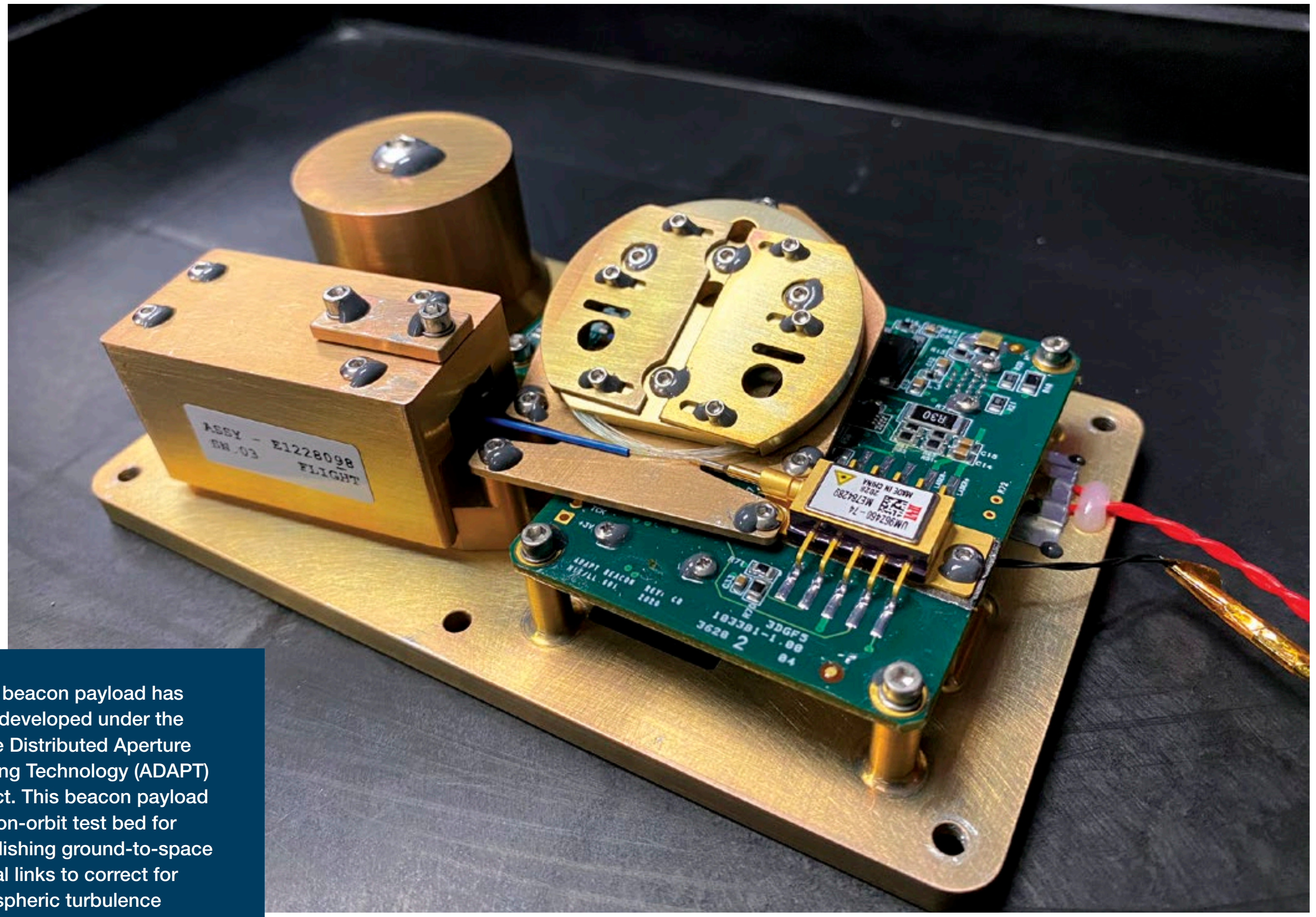
These shortcomings motivated the Resilient Mission Computer (RMC) project at Lincoln Laboratory. The project established a moonshot vision to build a foundationally secure computing system for operationally critical missions. In close collaboration with Howard Shrobe on MIT campus, the project team is addressing the root causes of cyber vulnerabilities in modern systems by focusing on three main pillars: building on security-aware hardware, incorporating safe programming languages, and reducing excess privilege in operating systems. The RMC and its follow-on project, called ARROWS for Advanced Resilient and Real-Time Open Weapon Systems, developed inventions and open-source prototypes that implement this vision across key layers of a computing stack. This project paves the way for future computer systems that are secure by design for use in the national power grid and nuclear command and control applications.

As a result of the RMC moonshot, the DARPA Information Science and Technology Study Group initiated a study called "Cyber Moonshot: Accelerating Security of Systems with Emerging Technologies." Co-chaired by Laboratory researcher Hamed Okhravi, the study will investigate advanced cybersecurity technologies and define future DARPA programs for deployment in critical defense systems.

At right, members of the Resilient Mission Computer (RMC) project (left to right: Hamed Okhravi, Samuel Mergendahl, Jason Martin, Nathan Burow) test a secure operating system design on a modern security-aware processor. To disseminate the RMC moonshoot vision, the team published a cover article, far right top, in the prestigious *IEEE Security & Privacy* journal.

>> Investments in Mission-Critical Technology, cont.

Optical Systems Technology



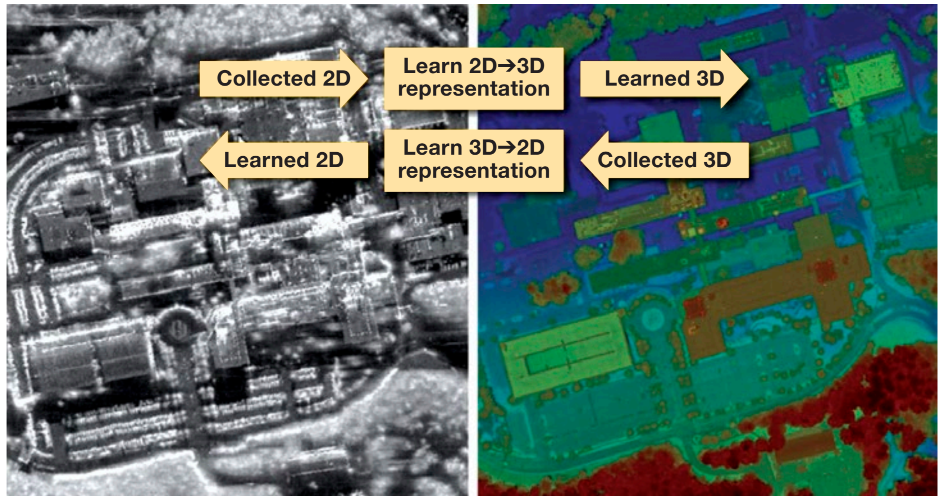
A ½U beacon payload has been developed under the Active Distributed Aperture Phasing Technology (ADAPT) project. This beacon payload is an on-orbit test bed for establishing ground-to-space optical links to correct for atmospheric turbulence effects by using a predictive adaptive optics technique. The ADAPT beacon carries a high-intensity laser diode to serve as a point-source phase reference, a photodiode to measure received optical power for validating an optical uplink, and a retroreflector to test target-in-loop phasing. The ADAPT beacon aims to chart a path for a low-cost and low–size, weight, and power (SWaP) unit, which has the potential to enhance optical communications for low-orbit satellites and other space-based laser applications.

Research into optical systems technology enables future mission capabilities in intelligence, surveillance, and reconnaissance (ISR) and communications. The goal of this research is to fill critical technology gaps in emerging DoD threat areas. Projects emphasize research in lidar, high-energy lasers, imaging systems, optical communications, and novel optical components. In 2021, the Laboratory conducted several notable efforts in optical systems:

- Designed a multiwavelength, multistatic, high-altitude lidar system for unmanned aerial vehicles (UAVs), with the mission of improving climate sensing and providing continual coverage of regional phenomena, including aerosol characterization, water vapor measurements, and wind measurements.
- Developed a space-based, globally persistent ISR architecture designed to enable orders-of-magnitude improvement in area coverage rate. This improvement is achieved by exploiting satellite constellations that have high revisit rates (minutes to seconds) and large field-of-regard sensors that use new day/night-capable midwave infrared detectors to improve resolution and sensitivity.
- Invested in a number of novel mission-enabling concepts. For example, research was conducted on a fundamentally different type of RF phased array receiver based on laser probing of room-temperature vapor cells in order to monitor Rydberg atom transitions in a gas.

Information, Computation, and Data Exploitation

Research in the information, computation, and data exploitation domain addresses challenges in the application of emerging artificial intelligence (AI) and big-data technology for national security needs. Topics of current research are AI algorithms and workflows, novel mission applications, data-intensive big-data computing, compute infrastructure, and approaches to advancing AI engineering practices for AI assurance. Projects undertaken in 2021 included the following:



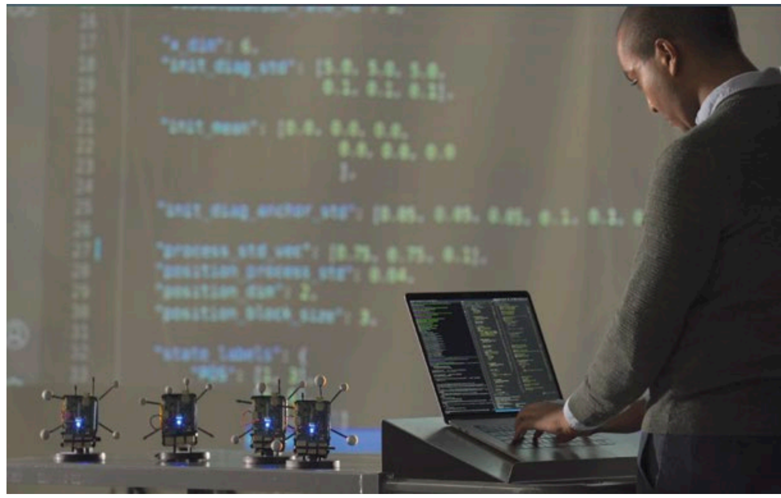
The Multimodal 3D Vision for Scene Interpretation project is working to improve single-modality interpretations through data augmentation that incorporates information from 3D data. The multimodality interpretation is then further improved through alignment and fusion with learned 2D-3D representations.

- Developed a resource-aware decision support framework for effective intervention and control of pandemics.
- Formulated new techniques that map AI applications to different classes of computing platforms such as embedded processors and large-scale data centers.
- Released as open-source a new software toolbox that enables the development of robust and reliable AI systems.

Radio-Frequency Systems

Research and development in RF systems is exploring innovative technologies and concepts in radar, signals intelligence, communications, and electronic warfare. Emerging national security challenges include a rapidly expanding threat spectrum, the integration of sensors on platforms with constrained payloads, operations in strong clutter and interference environments, detection and tracking of difficult targets, and robustness against sophisticated electronic countermeasures. To address these mission requirements, research projects focus on next-generation phased arrays, wideband and compact systems, and advanced algorithms. The 2021 projects included several noteworthy accomplishments:

- Advanced the state of the art in antenna technology to reduce form factor or cost, or to enable novel capabilities. For example, the Graded Index 3D-Printed Material Antennas project is using low-loss-graded index materials to create inhomogeneous permittivity in order to create wideband, multiband, and conformal RF systems.
- Continued development of the Polarimetric Interferometric Synthetic Aperture Radar, which will create a high-power, dual-polarized, dual-band active electronically scanned array panel targeting a unit-per-area cost that is 20% to 30% less than current state-of-the-art offerings.
- Designed a small-sized, low-power communication system that leverages commercially available components and novel network protocols to provide interference and jamming-robust networking for swarms of small UAVs.



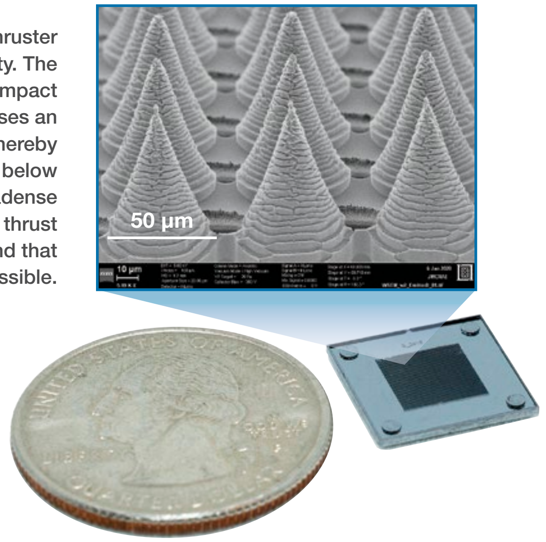
Pictured above is Eyassu Shimelis designing an experiment to demonstrate the performance of a set of low-cost, distributed sensing and transceiver nodes. The RF Network Sensing for Indoor Situational Awareness project is developing distributed sensing technology to help firefighters and first responders maintain situational awareness in challenging indoor environments. This design enables precision localization in indoor environments without relying on GPS.

>> Investments in Mission-Critical Technology, cont.

Integrated Systems

Projects in the integrated systems category bring together scientists and engineers to conduct applied research that accelerates the integration of advanced technologies into game-changing systems for national security. The goal is to demonstrate DoD-relevant system concepts that use novel architectures, recently developed component technologies, and new analytic methods. Several projects reached prototyping milestones in 2021:

- Developed a versatile satellite platform for rapid space technology demonstrations. This platform includes compact electric propulsion; automated guidance, navigation, and control for orbital maneuvers and station keeping; and a compact camera with on-board image processing. The satellite is designed to host experimental payloads (see ADAPT project on page 20) and is scheduled for its inaugural launch in spring 2022.
- Conducted towed helicopter flights of 3D diamond magnetometer navigation technology to measure magnetic, acoustic, and vibration noise. These data will help inform the design of the next-generation prototype. This magnetometer will enable platform navigation in environments where GPS is not available.
- Carried out studies of mission and application architectures to motivate advanced technology development for novel mission concepts. One example study is investigating a long-range X-ray inspection satellite for internal inspection of satellites on orbit.



In 2021, the Wafer-Scale Satellite team completed the assembly of the thruster module, consisting of an emitter chip with record-breaking emitter tip density. The increased emitter density increases thrust density while maintaining a compact form factor. An extractor is used to create a voltage difference, which causes an ion to emit from the emitter chip array and accelerate away from the array, thereby creating thrust. The team was able to keep extractor/emitter misalignments below 5 micrometers, which enabled the quantitative characterization of the ultradense electrospray thruster module. Initial diagnostics suggest that the module's thrust densities are competitive with state-of-the-art electrospray thrusters and that further increases in thrust density are possible.

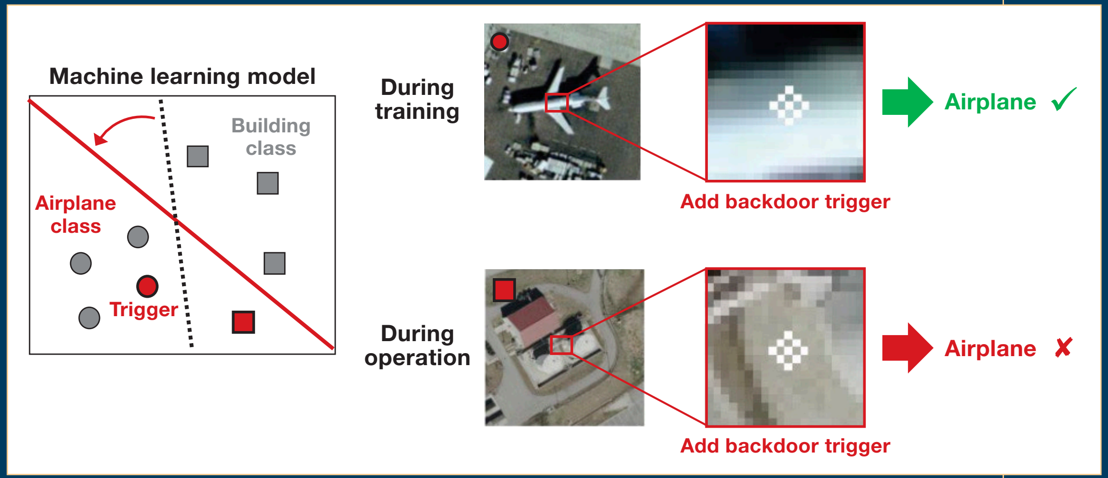
TECHNOLOGY HIGHLIGHT

Technology for the Information Age

Influence operations in social media have grown to become a critical concern in the United States, both in society and for national security. The Laboratory is developing a toolkit of advanced technologies that can help to discover where and when influence operations are being used, as well as how influence is generated and how it propagates. While the initial focus is on developing effective detection and assessment techniques, future focus will expand to include effective countering tools. Below are example projects striving to develop technologies that will allow the nation to respond to this threat:

Fake Data Generation

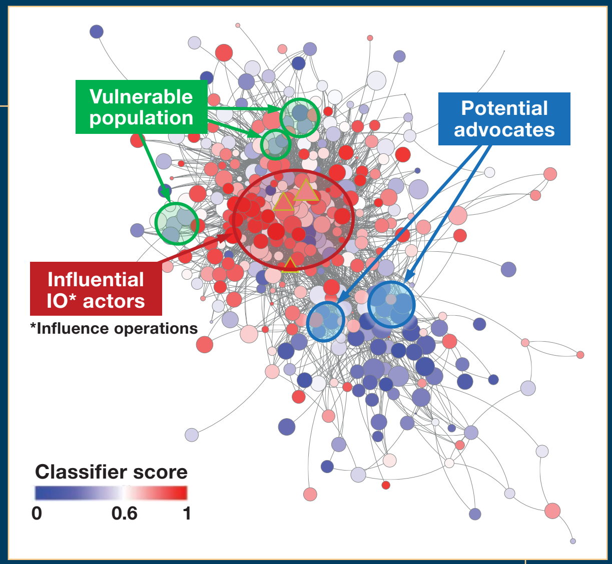
In 2021, the Technology Office hosted the FoolMe Challenge. Lincoln Laboratory staff were asked to submit ideas for the generation of a corpus of fake media/data of any type with relevance to national security. Two winners were funded to create, generate, or collect their proposed corpus of data, which will be used in a future hackathon-style challenge focusing on fake data detection and effects mitigation.



As machine learning is increasingly applied in the area of remote sensing, data-poisoning attacks can be developed to evade and mislead these systems. Data poisoning is an adversarial attack on a machine learning algorithm in which the data used to train the algorithm are manipulated or "poisoned" to cause the algorithm to fail in some manner. One of the FoolMe Challenge winners, the "Hiding in Plain Sight: Poisoning Attack to Remote Sensing Data" project, is using data-poisoning techniques that cause specific instances in a test set to be misclassified into a purposely inaccurate class.

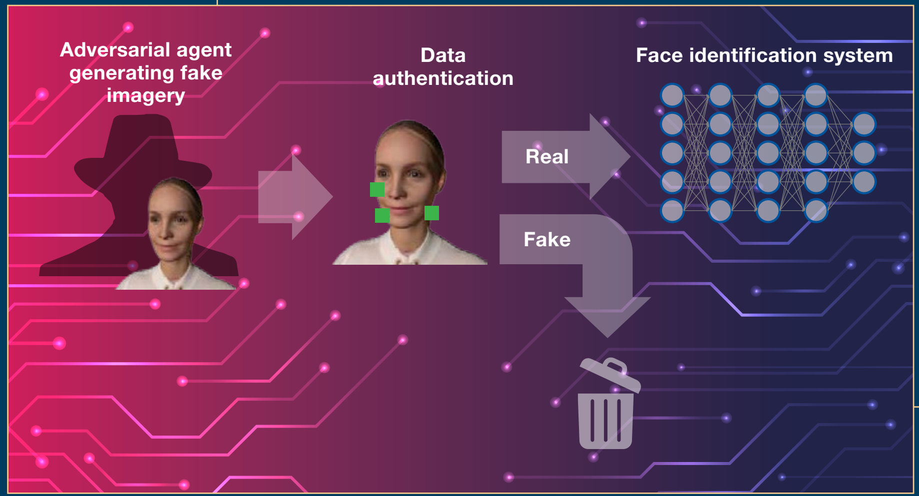
Impact Assessment Tools

The Reconnaissance of Influence Operations research team tested algorithms that assessed influence propagation against the known influence campaign carried out in the 2017 French presidential election. In the foreign Twitter propaganda network, algorithms classified network nodes (accounts) according to the degree of influence exhibited by each account. Circles indicate individual Twitter accounts, while larger red circles represent influential accounts that were likely part of the organized campaign to disseminate disinformation.



Fake Detection Tools

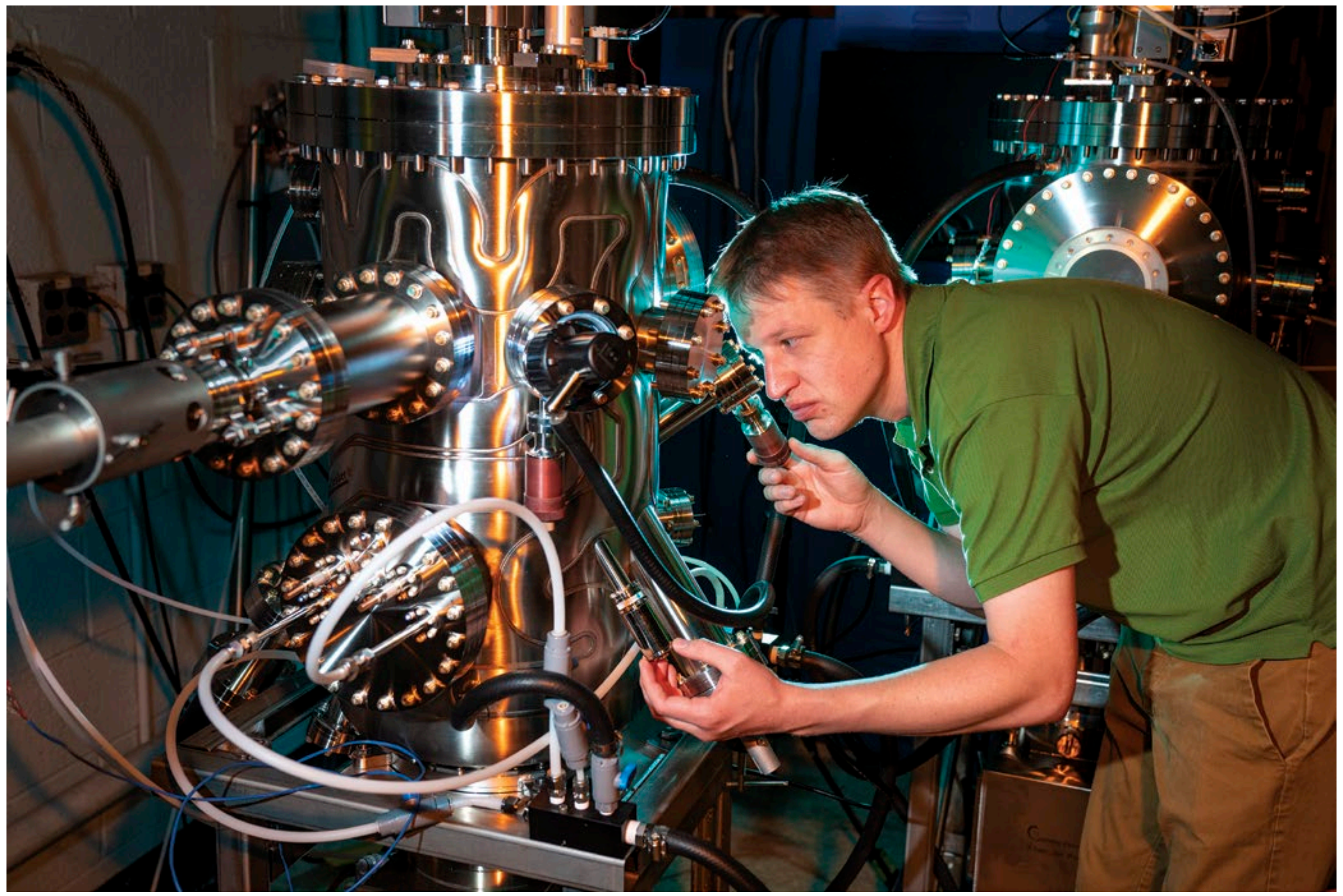
To better identify synthetic content before nefarious influence campaigns can use the content to spread disinformation, the Deepfake Gym project aims to strengthen the detection of deepfakes by addressing the poor performance of traditional techniques on novel instances, expanding new techniques to multiple modalities, and increasing the explainability of detection algorithms to increase user trust.



INVESTMENTS IN EMERGING TECHNOLOGY

Promoting research into technologies of growing importance to national security and the development of engineering solutions for projects in Lincoln Laboratory's relevant mission areas

Advanced Materials and Processes



The Materials-by-Design project is establishing a process for the accelerated discovery of materials for a wide range of applications, such as infrared windows for hypersonic aircraft and high-speed optical switches for lidar systems. Shown above is a new multimaterial synthesis tool that has been built under this project to facilitate rapid prototyping of a broad range of these new materials.

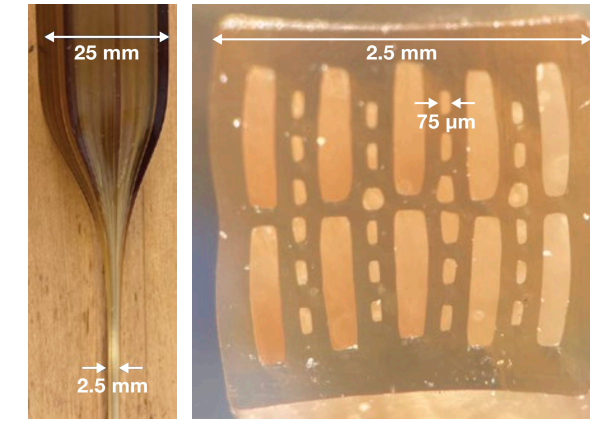
Research in advanced materials and processes seeks to invent materials and establish innovative processing capabilities to improve sensing, imaging, and manufacturing technologies for the nation. Efforts include the development of non-silicon electronic materials, advanced sensors, integrated microsystems, and advanced structures. In 2021, R&D in this area included several highlights:

- Continued to advance the Laboratory's ability to synthesize diamond with precise control over its material properties. These tailor-made diamonds are candidates to make fundamental advances in next-generation qubits for quantum computing and novel electronics.
- Leveraged heteroepitaxial growth (i.e., growth of non-silicon films on a silicon substrate) to combine high-performance lasers, modulators, and detectors with passive components based on various silicon-nitride compounds, on low-cost silicon substrates. The ability to use light instead of copper as high-density electronic interconnects for future computing hinges on this ability to combine disparate materials.
- Started development on a novel fiber battery that contains within an extruded fiber all active materials necessary to constitute a complete battery. This work is a step toward realizing advanced electronic textile threads, which have the potential to host complex computational circuitry.

Advanced Devices

Work in advanced devices focuses on developing novel components and capabilities to enable new system-level solutions to national security problems. Advanced devices span a wide range of fundamental technologies, including RF technology, lasers, advanced computing, imagers, and microsystems applications. Projects realized significant accomplishments in 2021:

- Characterized first-generation single-flux quantum (SFQ) circuit components and designed a second-generation SFQ digital focal plane array (DFPA) pixel that can be integrated into a 2D-array format. Such SFQ-based DFPA readout circuits are expected to simplify the room-temperature electronics and lower the SWaP of systems incorporating superconducting detectors, such as X-ray and gamma-ray spectrometers.
- Continued developing a superconducting amplifier array that will enable the detection of neutrinos having energies less than 100 electron volts by using a new, highly sensitive process based on measuring the energy involved in coherent neutrino scattering. Neutrino detectors that have improved sensitivity and reduced detector mass will benefit a variety of applications, including nuclear monitoring and basic science.
- Made progress on the hybrid integration of thin-film lithium niobate onto a photonic integrated circuit platform to realize a novel optical modulator with 65-gigahertz bandwidth and state-of-the-art sensitivity. Chip-scale millimeter-wave photonic signal processors offer the potential of processing RF signals with higher fidelity and lower SWaP than all-electronic solutions.



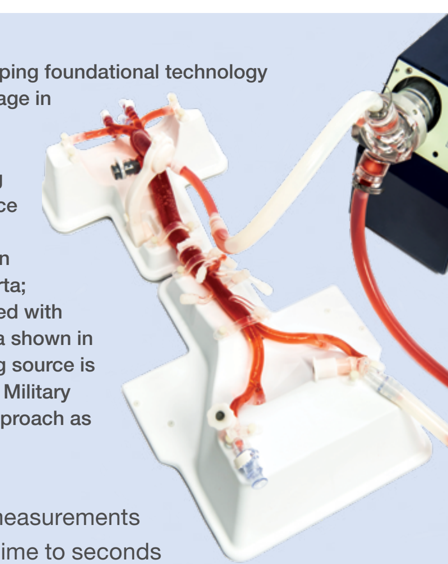
(a) (b)

The SWaP of chip-scale detectors and quantum sensors that require operation at cryogenic temperatures is limited by the large, inefficient refrigeration systems used to provide the cooling. The objective of the miniature cryocooler project is to reduce the SWaP of these cryo-refrigeration systems by developing microscale polymer-fiber heat exchangers. In FY21, liquid-nitrogen cooling (77 K) was demonstrated with a thermal-exchange effectiveness of > 90% through the development of a compact Joule-Thomson cryocooler incorporating a polymer-fiber-based heat exchanger. The images show the fiber preform assembly (a) and the cross-section of the resulting fiber (b).

Biomedical Science and Technology

Biomedical science and technology research at Lincoln Laboratory focuses on applied research into diagnostics and multidomain data analysis, biotechnology systems understanding and threat assessment, and human and team performance enhancement and optimization. This portfolio seeks to develop advanced biomedical technology and systems to address national health care needs and to enhance warfighter resilience and sustainability. In 2021, R&D in this domain achieved several milestones:

- Applied advanced AI methods to accelerate the development of antibodies for use against emergent pathogens. The methods take inspiration from state-of-the-art AI human language models to predict potentially efficacious antibody protein sequences. Preliminary results are very encouraging and show strong correlation with experimentally measured efficacy data.
- Continued development of a closed-loop, fluent, and intuitive ankle exoskeleton to support operators and warfighters in real-world environments, with the goal of reducing fatigue and increasing performance. Use of a muscle energy model derived from simple ultrasound measurements reduces personalization time to seconds instead of the typical hours of training time required.
- Made progress toward comprehensively characterizing breath samples in the aerosol and vapor regime. Such information could greatly improve researchers' and the medical community's understanding of disease detection, transmission, and potential mitigation strategies.

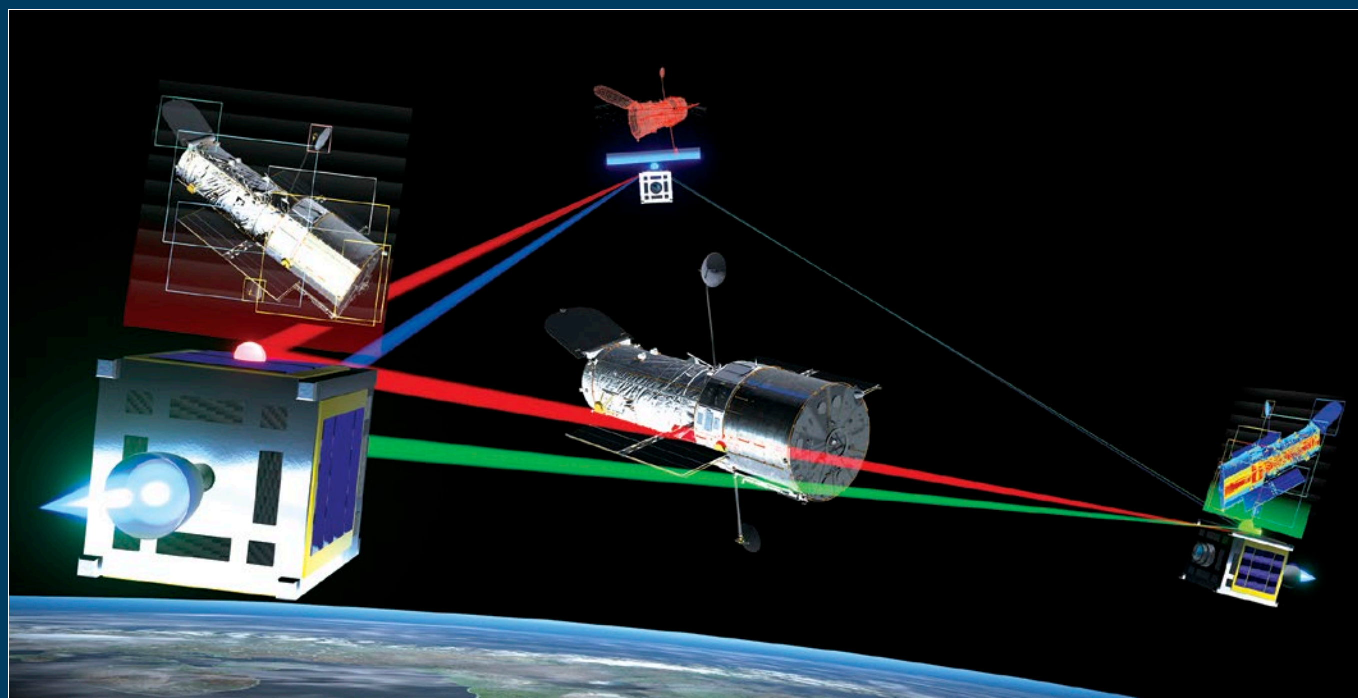


Lincoln Laboratory is developing foundational technology for managing torso hemorrhage in a pre-hospital environment. As part of that effort, researchers are investigating the hypothesis that the source of internal bleeding can be localized by using sensors on a catheter inserted in the aorta; this hypothesis is being tested with a physical model of the aorta shown in the photo. Once the bleeding source is localized, it can be stopped. Military medical experts view this approach as potentially transformational.

>> Investments in Emerging Technology, cont.

TECHNOLOGY HIGHLIGHT

Autonomy and Mobility in Space



The Multi-agent Autonomous Space Technology project seeks to develop autonomous space technologies for future missions in the space domain. This image shows a notional coordinated swarm of satellites that are using a variety of sensing modalities to survey and inspect a satellite.

Enabling autonomous coordination of multiple spacecraft can revolutionize the space domain. Such on-orbit autonomy requires satellite-based sensing for perception, decision-making, and control. While AI advancements are making it possible to achieve these tasks in space, testing such capabilities in space is expensive and difficult. To address these challenges, the Multi-agent Autonomous Space Technology (MAST) program is developing a space simulation tool to develop and train the necessary autonomy elements.

The simulator is designed to emulate complex engagements, rapidly generate high-fidelity sensor data, and interface with software architectures for large-scale training of AI algorithms. These data generated by the simulator are used to train algorithms to perform automatic segmentation of satellite components, and to develop decision-making algorithms for the control of satellite maneuvers and actions. While MAST is applying deep learning–based object detection and pose-estimation algorithms to solve the perception problem, advanced reinforcement learning methods are being developed to enable automated decision-making when satellite behavior is challenging to predict.

Exploration of space autonomy capabilities will help inform the Laboratory and its sponsors about feasibility and fruitful future research directions. In a broader context, MAST is part of a larger strategic plan investing in technologies for greater mobility and autonomy in space. For example, the Agile MicroSat project is developing a 6U satellite that can station-keep and maneuver in low-Earth orbit; the Wafer Scale Satellite project is investing in electrospray thrusters with ultrahigh thrust density; and the LORAX project is investigating a novel X-ray inspection concept that could rendezvous and inspect satellites on orbit.

Autonomous Systems

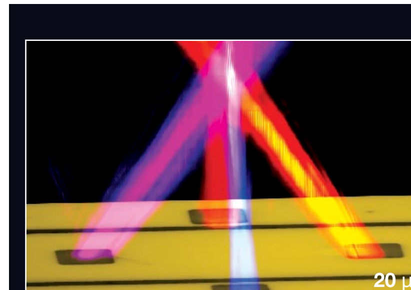
Systems with increasing degrees of autonomy are of growing importance to the DoD and other national security organizations. To address this emerging area, the Laboratory has pursued applied research focusing on intelligent perception and decision-making algorithms, multi-agent systems that include human-machine teaming, platform architectures, and the challenges of verification and validation. In 2021, the Laboratory made novel accomplishments in autonomy:

- Advanced real-time perception capabilities for low-SWaP systems. Semantic mapping algorithms were transitioned to a U.S. Army program to demonstrate novel UAV/unmanned ground vehicle (UGV) teaming concepts, and optical sensing algorithms were improved to extract higher-level knowledge of the environment (e.g., object or room identification).
- Evaluated the benefit of interpretability in a human-aware AI teaming algorithm and prototyped a novel, personalized scenario generator for accelerated tactics and training development. A path to transition the teaming algorithms and scenario generator to Navy training schoolhouses was also established.
- Created sonar imagery of multiple shipwrecks by using a prototype surface-based, distributed multi-input multi-output undersea mapping sparse sonar array (24 feet × 24 feet). A full-scale version of this prototype array is being designed and developed to support deep ocean floor mapping with a resolution two orders of magnitude higher than is currently achievable.

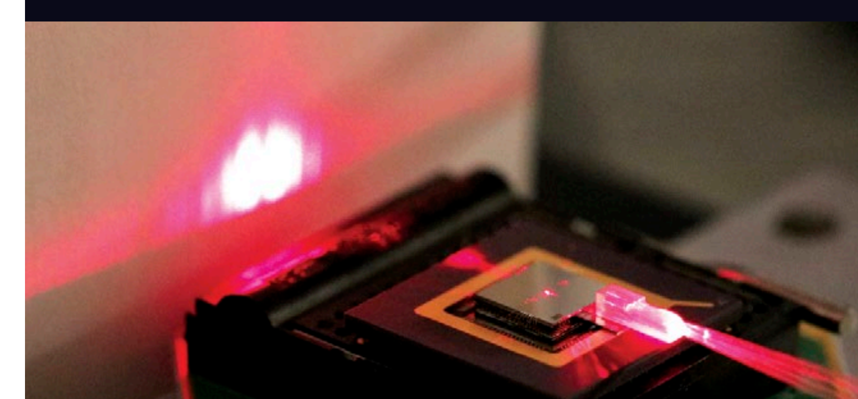
Quantum Systems and Science

Quantum systems can enable significant advances in sensing, communication, and computing. The Technology Office is investing in the next generation of these technologies, beyond the nearer-term focus of commercial efforts. In 2021, significant progress was made on a number of projects:

- Continued building an entanglement-based optical quantum network linking the locations of Lincoln Laboratory, MIT, and Harvard University. Networks require not only transport of information but also storage or memory. The Laboratory has demonstrated photonically addressable quantum memories that use defect centers in diamond to temporarily store the information carried by the photons that are used to communicate over the network. This memory system allows the network to extend over longer distances and to operate at greater data rates.
- Demonstrated for the first time a 3D integration of superconducting qubits by bringing together a high-coherence qubit, superconducting interconnect, and routing layers in a single device. As nascent quantum computers push from few-qubit experiments to test beds of moderate size and beyond, the architecture for addressing and controlling these qubits must also evolve.
- Developed a novel microwave-based readout technology that enables high-fidelity readout of large ensembles of nitrogen-vacancy color centers in diamond as they transition between quantum states under the influence of magnetic fields. Such color centers have emerged as a quantum system that can provide promising 3D-magnetometer technology. This readout technique extends beyond nitrogen-vacancy defects in diamond to enable efficient readout for a broad family of microwave-addressable solid-state systems.



As laboratory measurements of frequency become increasingly accurate, standards have started to shift from the microwave to the optical domain. Lincoln Laboratory is developing chip-integrated optical clocks in which electronic and laser-based control can be combined on a single fiber-optic-fed device. This year, the Laboratory combined optical ion traps with compact laser technologies to demonstrate optical clock operation that exceeds by two orders of magnitude the accuracy of existing portable microwave clocks.

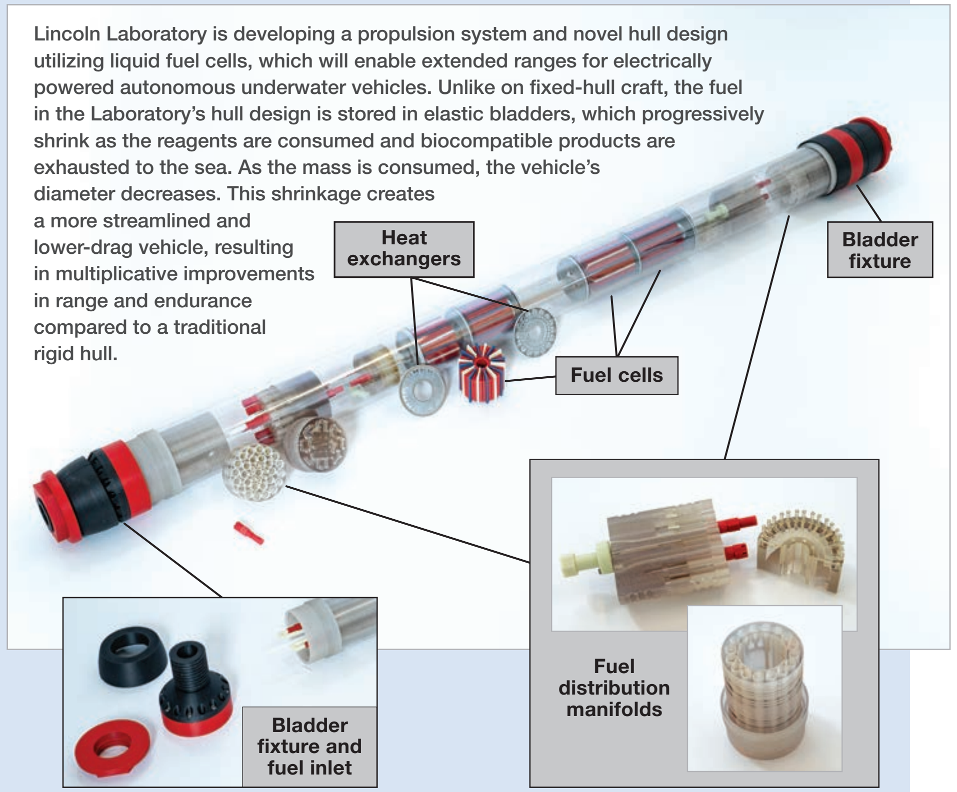


>> Investments in Emerging Technology, cont.

Energy

Research in this area supports DoD energy needs, including remote power, advanced energy storage, in situ resource harvesting, and reliability for microgrid systems up to the national grid scale. This year's work includes activities to address challenges such as advanced energy storage and novel platforms:

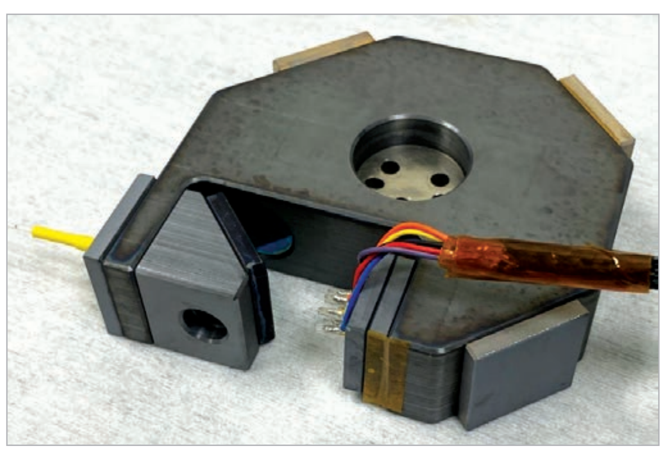
- Began development of an electrochemical power system based on liquid fluorinated reactants, which enable high energy density (33% higher than state-of-the-art lithium batteries) and intrinsically safe batteries tailored for undersea applications.
- Designed a high-voltage DC power train tailored for specific aerospace applications to reduce line losses and substantially reduce weight compared to AC/AC and AC/DC systems.
- Developed an affordable, secure, standardized, and easy-to-install set of devices to obtain telemetry from DoD facilities to support energy resilience exercises.



Lincoln Laboratory is developing a propulsion system and novel hull design utilizing liquid fuel cells, which will enable extended ranges for electrically powered autonomous underwater vehicles. Unlike on fixed-hull craft, the fuel in the Laboratory's hull design is stored in elastic bladders, which progressively shrink as the reagents are consumed and biocompatible products are exhausted to the sea. As the mass is consumed, the vehicle's diameter decreases. This shrinkage creates a more streamlined and lower-drag vehicle, resulting in multiplicative improvements in range and endurance compared to a traditional rigid hull.

Engineering

The Laboratory depends on state-of-the-art engineering capabilities to facilitate the development of advanced prototype systems. In the engineering area, technological investments are made in new tools and processes with the potential to enable new applications and to provide cross-cutting prototyping capabilities with broad applicability to Laboratory mission areas. In 2021, several efforts complemented this diverse portfolio:



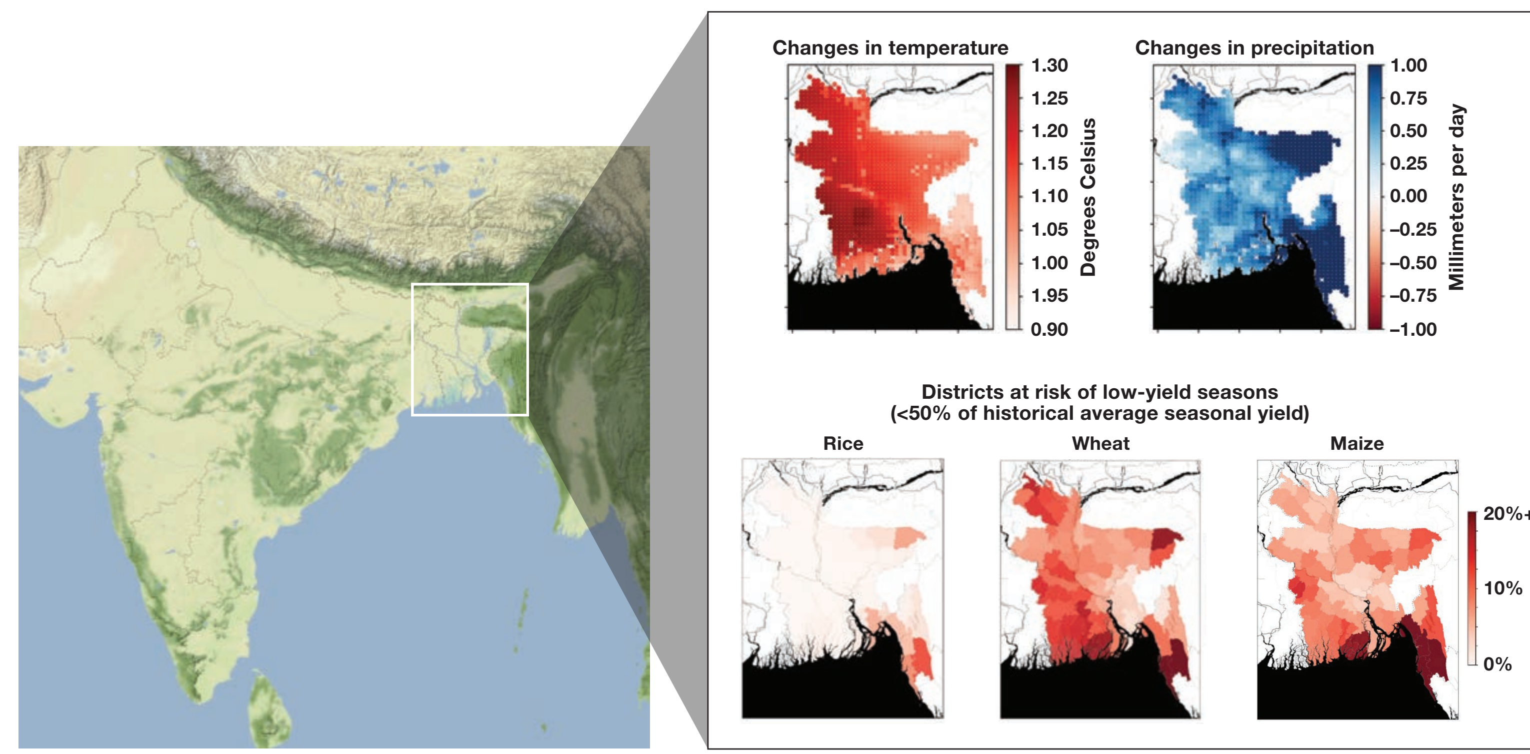
Often used as an optical substrate, single-crystal silicon (SCSi) is not typically thought of as a structural material. However, it has excellent optomechanical properties such as a high stiffness-to-weight ratio, a low coefficient of thermal expansion, and high thermal conductivity. Shown above is an assembly of a laser communication SCSi optical bench that looks to demonstrate both the feasibility and utility of using SCSi in next-generation low-SWaP optical payloads.

- Continued the multiyear investment to develop a digital engineering toolset known as LLIMAS (Lincoln Laboratory Integrated Modeling and Analysis Software) that integrates solid models with aero, thermal, structural, and optical design and analysis tools.
- Developed a prototype 3D printer that can embed copper-carbon nanotube composite conductors within complex thermoplastic structures to embed electronics within 3D-printed structures.
- Demonstrated two-phase heat transfer enhancements making use of microtexture, gasphilic surfaces that accelerate gas capture and release trapped vapors. This work was completed in association with the Varanasi Research Group on MIT campus.

Homeland Protection, Air Traffic Control, Humanitarian Assistance, and Disaster Relief

Investments in these areas emphasize both foundational research and infrastructure development needed to produce advanced capabilities applicable to a diverse set of critical national security needs. Investments support solutions to national challenges in air and ground transportation, land border and maritime security, chemical and biological defense, critical infrastructure protection, humanitarian assistance, and disaster response. Projects span research in advanced sensors and architectures, signal processing, data fusion, and decision support, as well as the development of experimental test beds and infrastructure needed to explore advanced concepts. Highlights from 2021 include such diverse projects as the following:

- Built an immersive pandemic simulator of passenger traffic within airports. The simulator includes infectious agent dispersion models and allows critical stakeholders to evaluate response strategies as a function of economic and transmission risks.
- Developed autonomous flight logic for a "chase drone" that tracks hostile autonomous unmanned systems back to their pilots and transmits photo/video for law enforcement identification.
- Continued developing an analysis architecture to assess the impact of urban air mobility on city/regional airspace and provided guidance on air traffic infrastructure requirements. Improvements in 2021 include the addition of hourly weather forecasting to capture gate holds and dynamic rerouting.



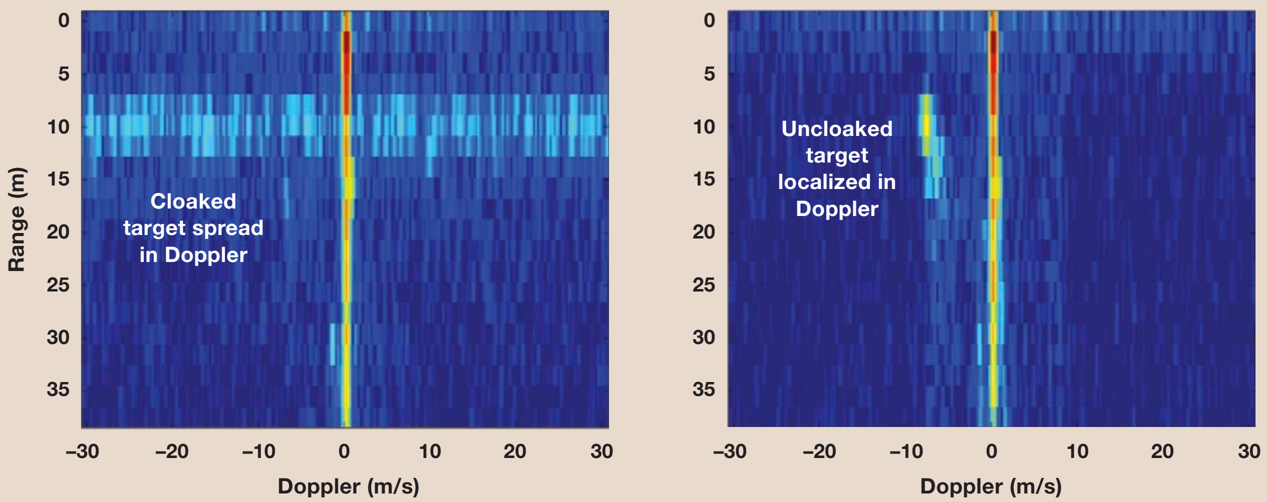
In 2021, a research team used the output of temperature and precipitation modeling as inputs to preliminary agriculture modeling of key crops in Bangladesh over a 30-year timespan. This work provides predictions of crop-yield impacts due to climate change, identifying districts at higher risk of having seasons with significantly reduced yields compared to historical data from 1975 to 2005. This agricultural modeling can be used to determine quantitative needs for adopting more flood- and heat-tolerant crops, different cropping patterns, and other resilient agricultural practices. Shown above are predictions of rice, wheat, and maize yields projected from 2021 to 2050 in Bangladesh.

INVESTMENTS IN INNOVATIVE RESEARCH

Providing support for R&D into foundational concepts and their applications in new systems

Seedlings

Through investments in seedling projects, the Technology Office allows staff to pursue innovative technology ideas and feasibility demonstrations. Seedlings encourage exploration of radically new approaches and technologies that could benefit Lincoln Laboratory's mission space.

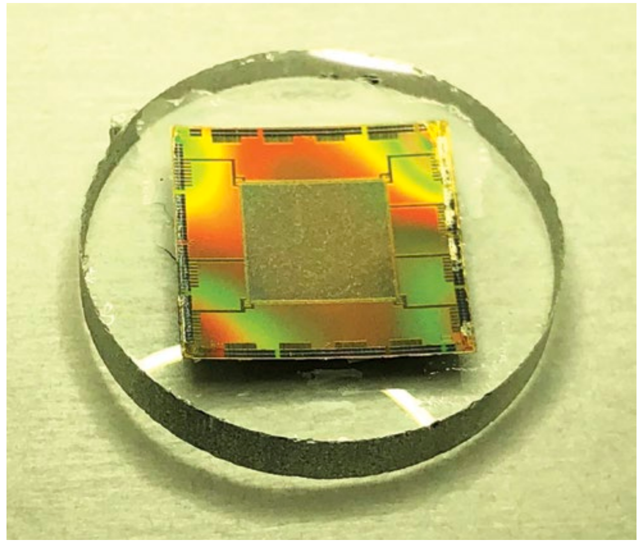


A Doppler cloak seedling project reduces the detectability of targets by spreading their radar return across Doppler bins. A proof-of-concept array was built and tested, demonstrating the basic Doppler cloak phenomenology with pulse repetition frequency–rate modulation. Higher speed modulation can spread the radar return over range bins as well.

Advanced Concepts Committee

The Advanced Concepts Committee (ACC) provides funding and technical and programmatic guidance for the development of basic and applied technology concepts that address important technical problems. The ACC funds a breadth of highly innovative, high-risk research that, if successful, has the potential for significant impact on the Laboratory's mission areas. A few notable 2021 projects are included below:

- Began working on a computational framework for predicting optimal designs and build paths of a space-based computer numerical control wire-bending concept to create multimaterial trusses that are strong, stiff, and thermally stable.
- Developed new, universal tools intended to counter and keep pace with the rapidly advancing field of deep learning–based steganography, a method of hiding data within images or audio files.
- Developed a wearable weave of stem-cell-seeded, biocompatible scaffold material to enable expedited recovery of injuries without sacrificing mobility.



Conventional planar focal plane arrays require complex optics to reduce spectral distortion and intensity rolloff at the edges of the array. A curved focal plane array would require simpler optics that could result in reduced size and weight for wide-field-of-view imaging applications. This ACC project, a collaboration between MIT, the University of Virginia, and Lincoln Laboratory, aims to demonstrate imaging arrays, such as the one shown above, that use novel flexible III-V detector material as a path toward curved imaging arrays.

FOSTERING INNOVATION AND COLLABORATION

Encouraging staff to discover and develop innovative technology by engaging in technical interchange meetings, conferences and seminars, and Technology Office challenges

Invited Speakers

In 2021, the Technology Office hosted virtual seminars to spark curiosity, creativity, and collaboration at the Laboratory. The speakers are renowned in their respective fields. Talks this year covered a diverse range of topics:

- Ramin Hasani from MIT's Computer Science and Artificial Intelligence Laboratory discussed novel continuous-time neural network models, called liquid time-constant networks.
- Reva Schwartz and Elham Tabassi of the National Institute of Standards and Technology discussed ways of identifying and managing bias in AI.
- Karen Riedl from Daimler presented on human-machine teaming and its role in vehicle production.
- Simon Knowles from Graphcore discussed the Colossus Mk2 processor, the M2000 Machine, and Graphcore's advancements in processors for machine intelligence.

Technology Office Chief Technology Officer Innovation Summit 2020

In November 2020, the Technology Office participated in and helped to coordinate the 5th Annual Chief Technology Officer (CTO) Innovation Summit. The Innovation Summit brings together the CTOs and associates from peer Federally Funded Research and Development Centers and University Affiliated Research Centers to share insights and ideas on tackling some of the nation's most challenging problems. Coordinating members included Lincoln Laboratory, MITRE Corporation, Draper Laboratory, Johns Hopkins University Applied Physics Laboratory, and this year's host organization, Aerospace Corporation. Representatives from government agencies, academia, nonprofit organizations, and industry are also invited to attend the summit.

The theme for this year's event was increased collaboration to address the rapidly changing landscape across the space enterprise and the multidomain operations it supports. The summit was held virtually and consisted of three days of invited speakers, panel discussion, and breakout discussions. Subthemes included strategies for responding to catastrophic climate threats, ensuring supply chain resilience, and collaborating to build the future of digital engineering.

Technology Office Challenges

The UnBIAS Challenge was launched to explore the emerging issues of algorithmic bias and fairness in the rapidly evolving world where AI applications are appearing widely.

Each year, the Technology Office invites staff to participate in challenges that explore topics relevant to the nation and the Laboratory's mission areas. In 2021, the Technology Office launched the Understanding Bias in Algorithms and Society (UnBIAS) Challenge, which focuses on educating the Lincoln Laboratory community about algorithmic bias, its manifestations, and its emerging impact on national security.

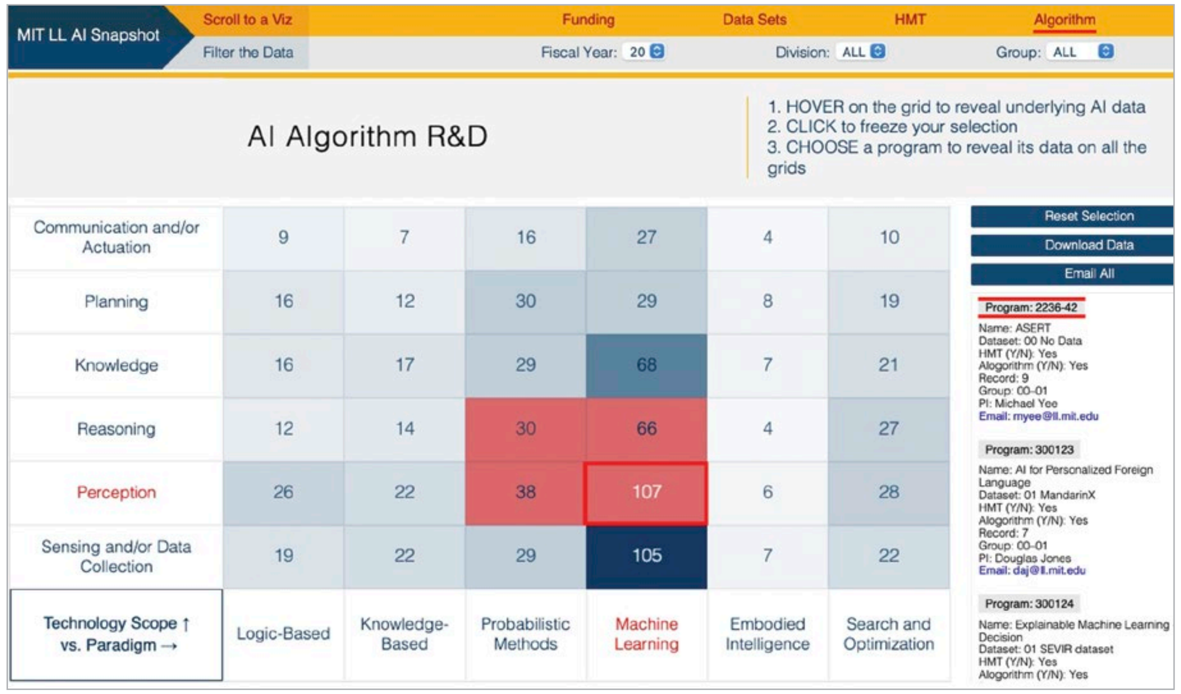
The initial phase of this challenge spans multiple months and consists of inviting speakers and holding virtual group discussions, coined the TO Coffee Talk series. The TO Coffee Talks are informal discussions with the Laboratory community on emergent topics of interest. Conversations are meant to encourage the sharing of thoughts and opinions and to foster a community of creativity and innovation.

ARTIFICIAL INTELLIGENCE AT THE LABORATORY

Research and development of AI-based capabilities spans all of Lincoln Laboratory's mission and technology areas. The Technology Office has undertaken the role of coordinating and strategically guiding various Laboratory-wide AI initiatives.

AI Snapshot Tool

Recognizing the strong potential for cross-cutting impact from advances in AI, the Technology Office put together a tool that captures AI initiatives at the Laboratory and highlights prevailing research thrust areas, the kinds of datasets that exist across mission areas, and associated technology readiness levels. Along with tracking the evolution and emergence of AI across the Laboratory, this tool helps inform researchers, developers, managers, and leaders about AI-related gaps, opportunities, and needs, which in turn helps shape future directions and investments.



Technology Scope ↑ vs. Paradigm →	Logic-Based	Knowledge-Based	Probabilistic Methods	Machine Learning	Embodied Intelligence	Search and Optimization
Communication and/or Actuation	9	7	16	27	4	10
Planning	16	12	30	29	8	19
Knowledge	16	17	29	68	7	21
Reasoning	12	14	30	66	4	27
Perception	26	22	38	107	6	28
Sensing and/or Data Collection	19	22	29	105	7	22

The AI Snapshot tool facilitates taking stock of the technology scope and paradigm of AI algorithm development at the Laboratory, in addition to providing many other programmatic and technical details. By using this tool, the Laboratory can assess emerging and near-term trends and compare them to anticipated strategic directions for AI R&D. For example, today, machine learning for perception is a prevailing research direction, but reasoning applications are also an emerging research area.

Laboratory-wide AI Initiative

To facilitate intersecting technology development, in 2018, the Laboratory stood up the AI Technology Group under the direction of the Technology Office. Since then, Lincoln Laboratory's strategic initiative in AI technology has made substantial progress in advancing AI technologies and has continued to address complex challenges facing the nation and the world. This year in particular, the Laboratory conducted both fundamental and applied AI research to assure AI systems are trustworthy and mission-ready, and developed several general-purpose AI software tools to address challenges in AI-system engineering. Below are examples of 2021 accomplishments from projects with broad AI purview:

- Developed and released an initial version of an open-source responsible AI toolbox that will facilitate evaluation and enhancement of AI model robustness, resilience, and explainability. Tools recently developed include components for uncertainty-aware learning for detecting outliers, anomalies, attacks, and distribution shifts.
- Developed open and interpretable interfaces for machine learning–based decision support systems in operational workflows. In collaboration with Air Force CyberWorx, the Laboratory developed a framework for characterizing stakeholder explainability needs.
- Conducted a comprehensive study of AI ethics, using security clearance processing as a use case, and created a set of best practices for improving fairness and transparency in the design, development, and assessment of AI systems.

AI Technical Interchanges

RAAINS Workshop

The Laboratory virtually hosted the second annual Recent Advances in Artificial Intelligence for National Security Workshop (RAAINS), which focused on the state of the art in key areas of AI, recent advances applied to national security, and future directions in AI that are specifically of interest to the DoD and the Intelligence Community. The workshop engaged a diverse audience with excellent keynote speeches, presentations, and virtual posters. Attendees were also offered the opportunity to take several online courses in natural language processing, computer vision, autonomy, human-machine collaboration, and AI for biology.

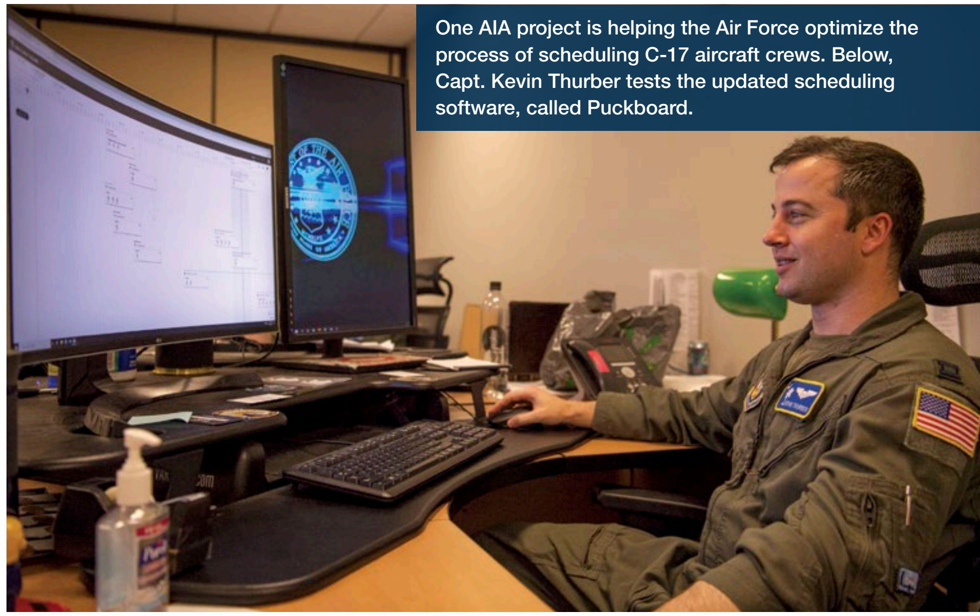
This year, the Human Machine Collaboration for National Security Workshop was hosted in conjunction with RAAINS. The workshop focused on the theme of human-machine teaming and addressed intelligent AI-based solutions, the interface with humans, and a radical rethinking of mission workflows as AI assumes a peer relationship with operators.

Human-Machine Teaming Technical Interchange Meeting

Recognizing that teaming between humans and machines is a critical aspect for many AI systems and that AI-based technologies are being developed across all Laboratory mission areas, the Technology Office hosted a Laboratory-wide technical interchange meeting to share insights into the roles and relationships between human and machines in current and future national security systems. The meeting engaged a diverse Laboratory audience with overview presentations by each division and lightning talks that shared future concepts of enabling technologies.

Department of the Air Force–MIT Artificial Intelligence Accelerator

The Laboratory, with the Air Force, has continued to engage with MIT to create new algorithms and AI solutions that will improve Air Force operations while also addressing broader societal needs. Several projects are underway that span a wide range of AI topics and applications, including an effort to help train and strengthen the DoD AI workforce. The Department of the Air Force–MIT AI Accelerator (AIA) launched a new exploratory project called Know-Apply-Lead that aims to advance educational research activities that promote maximum learning outcomes at scale for learners with diverse roles and educational backgrounds, ranging from Air Force and DoD personnel to the general public. The project team will research and evaluate various pedagogical practices and learning benefits associated with training Air Force personnel in AI topics over a variety of existing courses, map out the landscape of educational needs and competencies, and pilot experimental learning experiences with the goal of outlining early prototypes for innovative technology-enabled training and learning. The research is expected to provide insights that will benefit AI learners across the nation while supporting the DoD's objective to develop elite and world-class AI-ready services.



One AIA project is helping the Air Force optimize the process of scheduling C-17 aircraft crews. Below, Capt. Kevin Thurber tests the updated scheduling software, called Puckboard.

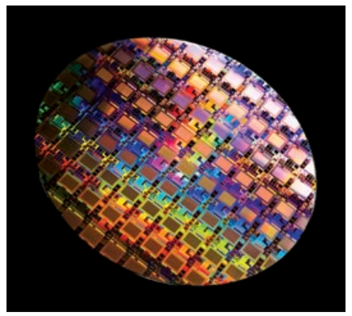
Informed AI Seedling

A strategic study was conducted to position the Laboratory to better understand how to leverage AI techniques that exploit both data and domain expertise (including scientific knowledge). In particular, informed deep learning techniques promise to further advance the state of the art in AI via significant performance improvements, and to broaden AI's applicability beyond its current reach across Laboratory mission areas. The study identified technology gaps, mission application opportunities, and strategic investment opportunities.

R&D 100 Awards

R&D World magazine presented 2021 R&D 100 Awards to nine technologies developed by Lincoln Laboratory researchers, either solely or in partnership with other organizations. These awards recognize 100 groundbreaking technological innovations developed by research institutes and companies worldwide and introduced during the prior year. From hundreds of nominees, the winners are selected by an international panel of expert judges from academia, industry, and national laboratories.

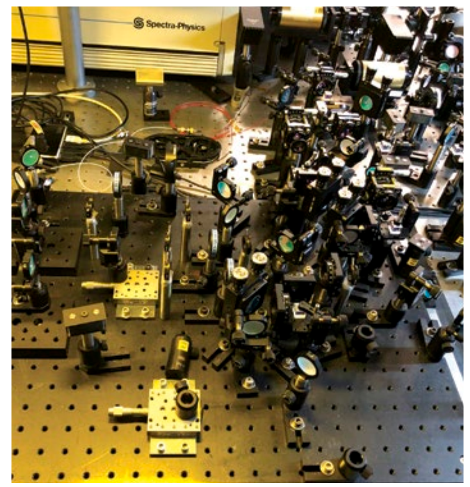
Field-Programmable Imaging Array



A universal digital back end for camera systems which, when hybridized to an image detector array, results in a flexible and powerful digital processing system-in-package.

LINCOLN LABORATORY TEAM: Valerie Finnemeyer, Jonathan Frechette, and Richard Younger, project leads; Farhan Adil, Phillip Bailey, Maria Blood, Suzanne Burzyk, Hernan Castro, Stefan Chase, Tom Cheng, Robert D'Ambra, Eric Dauler Kaitlyn Dixon, Erik Duerr, Thomas Ferguson, Timothy Gagnon, Matthew Gregory, Peter Grossmann, Austin Holloway, George Jordy, Thomas Karolyshyn, Anthony Kryzak, Jordan Lahanas, George Lambert, Renee Lambert, Sandra Lee, Jonathan Leu, Jerry Lipson, Daniel Ripin, Gregory Rowe, Daniel Santiago, Kenneth Sims, Timothy Smith, Antonio Soares, Matthew Stamplis, Elaine Swenson, Kate Thurmer, Brian Tyrrell, David Volfson, Donna-Ruth Yost, and Brian Yu

Free-space Quantum Network Link Architecture



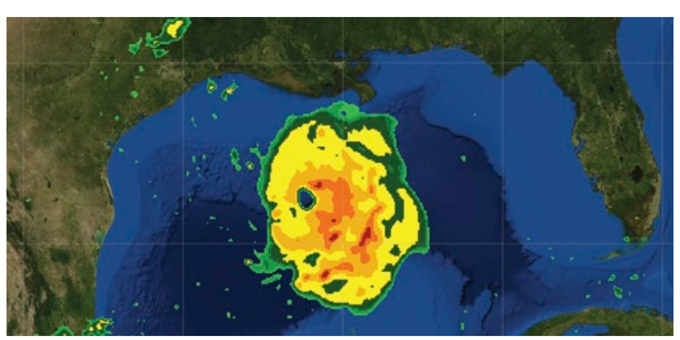
A system that enables the generation, distribution, and remote interaction of entangled photons across free-space links.

LINCOLN LABORATORY TEAM: P. Benjamin Dixon and Catherine Lee, project leads; Don Boroson, Matthew Grein, Scott Hamilton, Ryan Murphy, Katia Shtyrkova, and Neal Spellmeyer

Global Synthetic Weather Radar

A technology that provides radar-like weather imagery and radar-forward forecasts in global regions where actual weather radar are not deployed or are limited in range.

LINCOLN LABORATORY TEAM: Haig Iskenderian and Mark Veillette, project leads; Ashish Banerjee, Richard Ferris, Richard Knowles, Nikhil Kotecha, Patrick Lamey, Artyom Manwelyan, Danielle Morse, Alexander Proschitsky, Shibi Rajagopalan, and Mark Worris



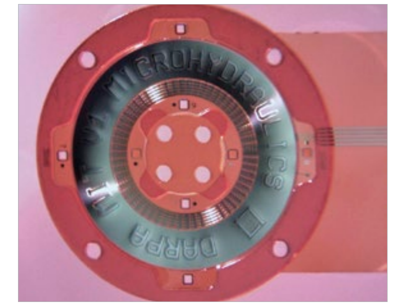
Guided Ultrasound Intervention Device

A handheld tool, utilizing real-time AI software, that enables a medic to rapidly and accurately catheterize a central vein or artery in a pre-hospital environment.

LINCOLN LABORATORY TEAM: Laura Brattain and Brian Telfer, project leads; Nancy DeLosa, Jay Gupta, Matthew Johnson, and Joshua Werblin

Microhydraulic Motors

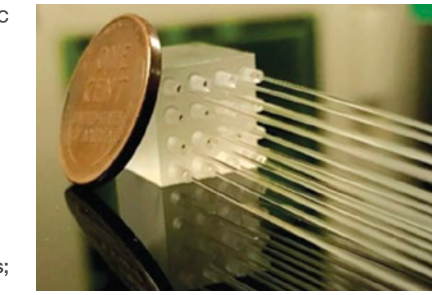
A scalable, electrowetting-based actuation platform with a torque density two orders of magnitude higher than that of electric motors.



LINCOLN LABORATORY TEAM: Jakub Kedzierski, project lead; Hero Chea

Monolithic Fiber Array Launcher

An all-glass, monolithic fiber array launcher that is smaller and more robust than standard arrays.



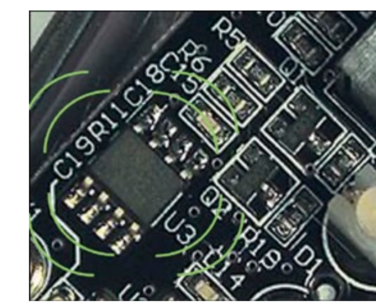
LINCOLN LABORATORY TEAM: Daniel Miller and John Nowak, project leads; Gregory Cappiello, Jeffery Fuller, Patrick Hassett, Christopher Holt, Christopher Hwang, Eric Lepowsky, George Ni, and Joshua Olitzky

Motion Under Rubble Measured Using Radar

A lightweight, portable life-detection radar that rapidly senses, ranges, and characterizes survivors trapped beneath rubble.

LINCOLN LABORATORY TEAM: Kate Byrd, Raoul Ouedraogo, George Pantazis, Adrienne Sands, and Andres Sisneros, project leads; Curtis Davis, Brian Day, Kimberly Holmgren, Anthony Ingano, Craig Keim, John Kinney Jeffery Lim, Danielle Mathews, David Maurer, Robert Morrison Jr., Eric Phelps, Nandini Rajan, Dana Spinuzzi, Marc Vaillant, and Javona White Bear

Spectrally Efficient Digital Logic



A set of digital logic families that operate with intrinsically low electromagnetic interference emissions.

LINCOLN LABORATORY TEAM: Robert Murphy, project lead

Traffic Flow Impact Tool

A tool for air traffic control managers that predicts and displays impacts to airspace capacities and traffic flow rates during convective weather.

LINCOLN LABORATORY TEAM: Michael Matthews, Mark Veillette, Joseph Venuti, and Mark Worris, project leads; Kim Calden, Bradley Crowe, Richard DeLaura, Peter Erickson, James Evans, Fulvio Fabrizi, Richard Ferris, James Kuchar, Danielle Morse, Lauran Owirka, James Pelagatti, and Tom Reynolds

Technology Transfer

Lincoln Laboratory engages in the development and demonstration of advanced prototype technologies and systems, with the overall objective of transferring these capabilities to the government, industry, and private sector. These transfers include hardware, software, materials, technical data, and subject-matter expertise and provide a diverse and resilient set of national security capabilities while contributing to the economic, environmental, and social wellbeing of the United States.

Leading and directing mission-based research at the intersection of government, academia, and industry requires Laboratory staff to publicize research results in technical reports, in peer-reviewed journal articles, and at conferences and technical seminars. Staff members are encouraged to promptly disclose new subject inventions and software, and, working with MIT's Technology Licensing Office, have developed a strong portfolio of patents and copyrighted materials in all the Laboratory's primary technical domains. Inventions and copyrighted works carry certain government-use rights and are frequently also promoted for transition to the private sector via open-source or commercial licensing. These activities promote information sharing and accelerate innovations from concept to practice, closing the gap between the research and the technology's adoption for national security and societal benefit.

FISCAL YEAR 2021 — TECHNOLOGY TRANSFER BY THE NUMBERS

103 Articles in technical journals	**65** Papers in published proceedings	**54** Patents issued
19 Lincoln Laboratory–hosted conferences	**104** Technology disclosures filed	**9** R&D 100 Awards

THE TECHNOLOGY VENTURES OFFICE

The Technology Ventures Office (TVO) was established in 2018 to provide strategic coordination for technology transfer–related activities at the Laboratory.

The TVO works to promote the broadest possible impact of Lincoln Laboratory innovation by facilitating the inflow and outflow of advanced technology. The TVO focuses in a few distinct but related areas:

- Facilitating and tracking sponsor-directed technology transition so that the Laboratory products of government-funded R&D can be rapidly accessed by others
- Engaging the commercial sector in collaborative R&D that creates new markets for Laboratory-developed technologies and that invites new (often nontraditional) businesses to work with the Laboratory in support of its national security mission
- Formulating intellectual property strategies that, through commercialization, promote government and private-sector access to Laboratory-developed capabilities
- Leveraging nonfederal funding opportunities to expand the societal and environmental impact of Laboratory expertise, knowledge, and technologies

LEADERSHIP (Left to right)
Dr. Teresa Fazio, Ventures Officer
Dr. R. Louis Bellaire, Deputy Technology Ventures Officer
Dr. Bernadette Johnson, Chief Technology Ventures Officer
Jennifer A. Falciglia, Program Manager

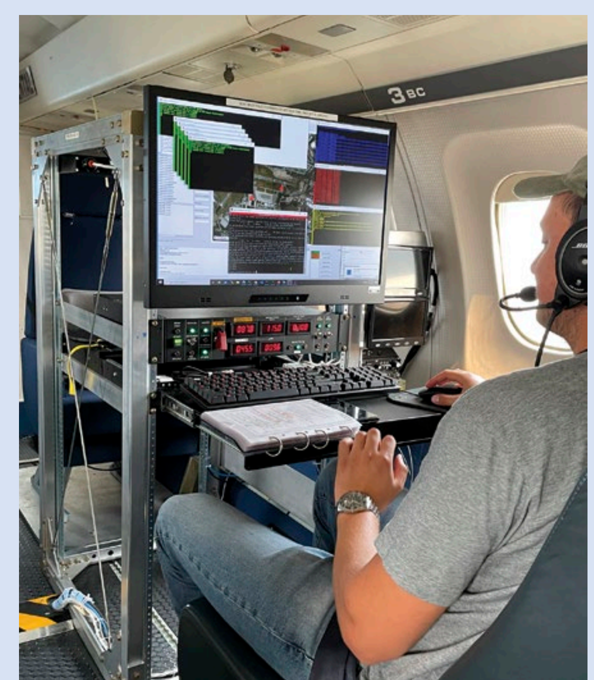
SPONSOR-DIRECTED TECHNOLOGY TRANSITION

Lincoln Laboratory has a history of commitment to developing prototype technologies that support government acquisition program and procurement contract awards. The Laboratory is also frequently called on to deliver quick-response capabilities to respond to urgent operational needs and humanitarian emergencies.

Since the TVO was established, one of its foci has been to optimize the process by which the Laboratory effectively transitions its technologies to others at the government's request. In the TVO's first two years, new guidelines and a simplified government-directed transfer agreement process were established to facilitate such actions, and all transfers were recorded and tracked in a dedicated database. The database allows the TVO to conduct analytic assessments and supports more sophisticated portfolio analyses by benchmarking transfer activities and identifying trends. In 2021, the TVO's third year, the emphasis has been on capturing technology transfer intent at the beginning of a program so that industry partners are readily available for handoffs and so that industry best practices can be deployed early in the technology development lifecycle.

This focus resulted from conversations with government sponsors and from observations of the value in forming a transition plan early in the program and identifying and resolving barriers.

In addition, the TVO consulted with Federally Funded Research and Development Centers (FFRDCs), University Affiliated Research Centers (UARCs), and other nonprofit peer institutions throughout the year to identify best practices at similar organizations that could be adopted at Lincoln Laboratory. These collaborations have promoted the dissemination of collective strategies and facilitated creative solutions for chronic and newly identified issues, including those surrounding patent-cost reimbursements and licensing of federally funded research products.



Spotlight: Accelerated ISR Capability Acquisition

The Laboratory's Mode Development Kit (MDK) accelerates the integration of new sensors and subsystems and promotes flexible acquisition of future intelligence, surveillance, and reconnaissance (ISR) capabilities. The MDK is based on the Common Open Architecture Radar Programs standard, whose general goal is rapid and cost-effective capability acquisition and improvement. Providing the software infrastructure, tools, and examples, the MDK reduces barriers to entry (such as cost and access) to third-party developers and encourages broader engagement, increased competition, and new capabilities. The sponsor-directed transfer of the MDK software has benefitted 10 commercial and nonprofit organizations in 2021 alone.

Shown at left is open-architecture, real-time radar mode software being exercised on the Airborne Radar Testbed.

>> *Technology Transfer, cont.*

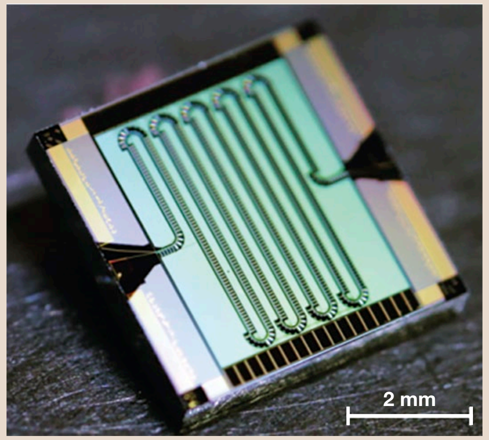
Interacting with the Commercial Sector

Lincoln Laboratory engages with the commercial sector on several fronts to maximize the economic and societal impacts of its research by transitioning prototype innovations into real-world products. Partnering with industry can create new value and new markets as federally funded capabilities are adapted to private-sector needs and vice versa. In FY2021, the Laboratory conducted collaborative R&D with 16 companies under Cooperative Research and Development Agreements (CRADAs). These R&D partnerships are funded by industry to advance dual-use or commercial technology development. CRADAs are an important mechanism by which the private sector benefits from original investments by the U.S. government. The Laboratory also executed 23 Collaboration Agreements with multiple not-for-profit institutions and an additional 25 research collaborations directly with MIT faculty and research staff. These collaborations often advance the state of early-stage technology development for applications that encompass all the Laboratory's mission areas.

One important form of commercial engagement is the Laboratory's direct partnerships with qualified small businesses to conduct R&D that addresses specific government needs. In 2021, Lincoln Laboratory executed 16 Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) projects under sponsorship from government agencies such as the U.S. Navy, DARPA, NASA, Department of Energy, and U.S. Special Operations Command. The Laboratory continues to directly support small businesses through R&D subcontracting. Since 2018, the Laboratory has implemented a customized variant of the Commercial Solutions Openings (CSOs), which are flexible technology development solicitations and contract awards that support nontraditional companies. The CSOs allow the Laboratory to rapidly seek commercial capabilities that cost-effectively address pernicious challenges confronting the Laboratory's diverse sponsor base. Two CSOs were completed in FY2021, both in the energy sector.

A challenge the TVO continues to address is how to identify and attract capable companies that can enrich the Laboratory's R&D capabilities and serve as transition partners for technologies developed at the Laboratory. The "Partner with Us" portal on the Lincoln Laboratory website allows a company to view standard contractual agreements, explore mechanisms for collaborative engagements, and browse SBIR/STTR collaboration topics that align with areas of Laboratory expertise. The Laboratory is growing outreach activities by participating in industry-focused events, including those directed at small businesses, and publicizing on the website dual-use technologies available for licensing or further development.

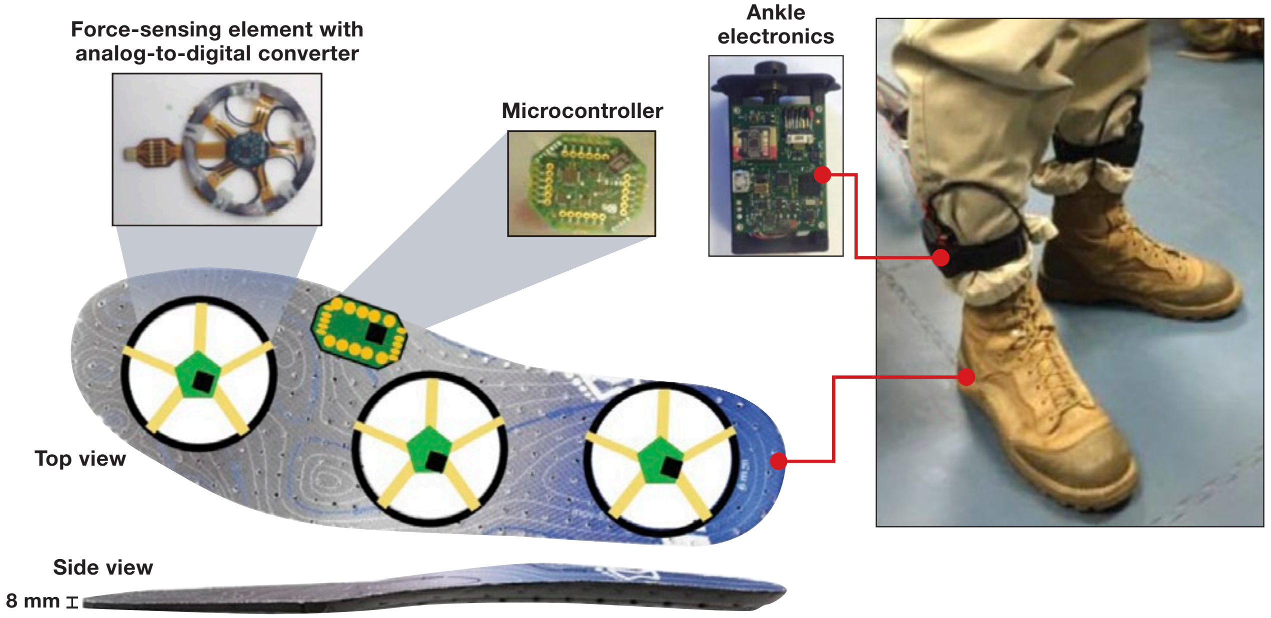
Spotlight: Quantum Computing CRADAs



The Laboratory developed and delivered to research partners traveling-wave parametric amplifiers like the one shown above.

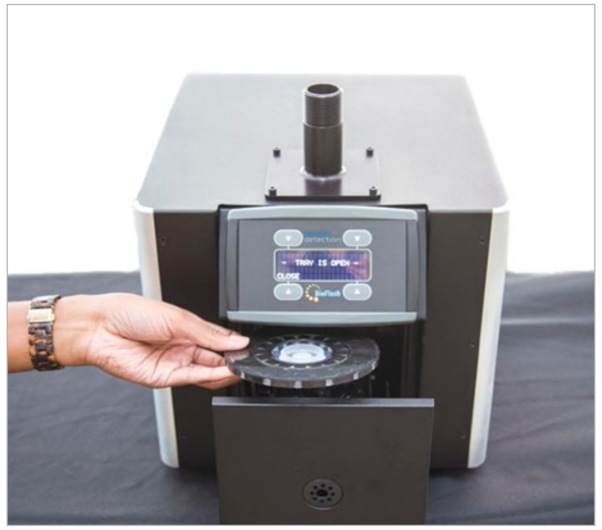
MIT has developed the world's most advanced integrated circuit fabrication process for superconducting electronics. With consent from government sponsors, the Laboratory has delivered more than 200 traveling-wave parametric amplifiers to 50 leading strategic quantum research partners in the United States and internationally. These CRADA partners seek to ascertain the utility of these superconducting amplifiers in enabling broadband, high-efficiency readout of multiple quantum bits (qubits). Advances in this technology are a key stepping stone to creating large-scale quantum computers.

Spotlight: Defense Innovation Accelerator



The MoBILE shoe insert includes load- and force-sensing elements positioned at the heel, arch, and toe of the foot. The insert's microcontroller measures acceleration and body orientation. The ankle electronics process data from several sensors.

The Department of Defense's National Security Innovation Network Defense Innovation Accelerator matches cutting-edge technologies sourced from the Defense Laboratory Enterprise with entrepreneurs to facilitate technology transition to the private sector. From a pool of more than 450 technologies submitted in the FY21 solicitation, 22 were enrolled into a nine-month accelerator program, including three technologies from Lincoln Laboratory: MoBILE (Mobility and Biomechanics Insert for Load Evaluation, shown in the photo above), Cyber Sensing for Detecting Power Outages, and AI-Enabled Sonar Detection of Underwater Objects. ELVEE, the nascent startup team based on MoBILE, won the Pitch Day competition at the end of the program.



Spotlight: Smiths Detection Receives Expanded CANARY Technology License

Smiths Detection, a global leader in threat detection and security screening technologies, has expanded the company's field-of-use licensing of the CANARY (for Cellular Analysis and Notification of Antigen Risks and Yields) biosensor technology developed by MIT and Lincoln Laboratory staff. This technology, originally developed to combat bioterrorism, is capable of rapidly detecting pathogens with high sensitivity and specificity. Smiths' expanded exclusive commercial license will enable new point-of-care diagnostic applications initially focusing on a SARS-CoV-2 biosensor.

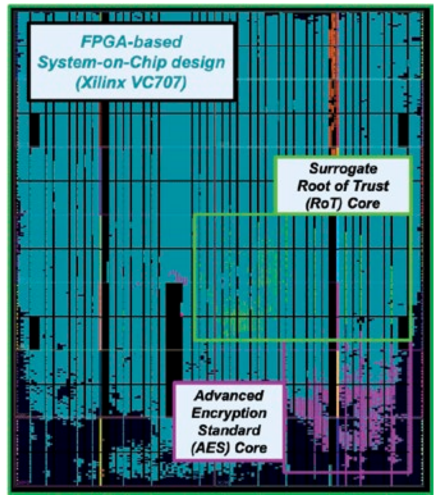
The photo at left shows Smiths Detection's BioFlash Biological Identifier, which uses CANARY technology. Image: Smiths Detection

>> Technology Transfer, cont.

Intellectual Property Management

MIT is one of the world's leading institutions in intellectual property disclosures and patenting. MIT's Technology Licensing Office works closely with the TVO to implement strategies and policies for protecting federally sponsored intellectual property. In 2021, 14% of MIT's technology disclosures were submitted by Lincoln Laboratory; on average, 69% of Laboratory disclosures result in at least one patent filing, and 72% convert to at least one patent grant. Copyright-protected software and non-software technical data comprised 52% of all disclosures in 2021. Approximately 58% of this year's disclosures were submitted by first-time contributors, highlighting the Laboratory's ongoing effort to create a vibrant and inclusive community for inventors and authors.

In accordance with objectives and guidance from the Department of Defense, sponsors continue to make significant use of open source as a licensing and distribution method. By open-source licensing of key technologies, technical priorities are signaled; ecosystems are built; emerging technology solutions and standards are promoted; and methods and practices are created through collaborative engagement with academic, government, and commercial partners. In 2021, the Laboratory added 33 new open-source projects, growing the portfolio by one-third.

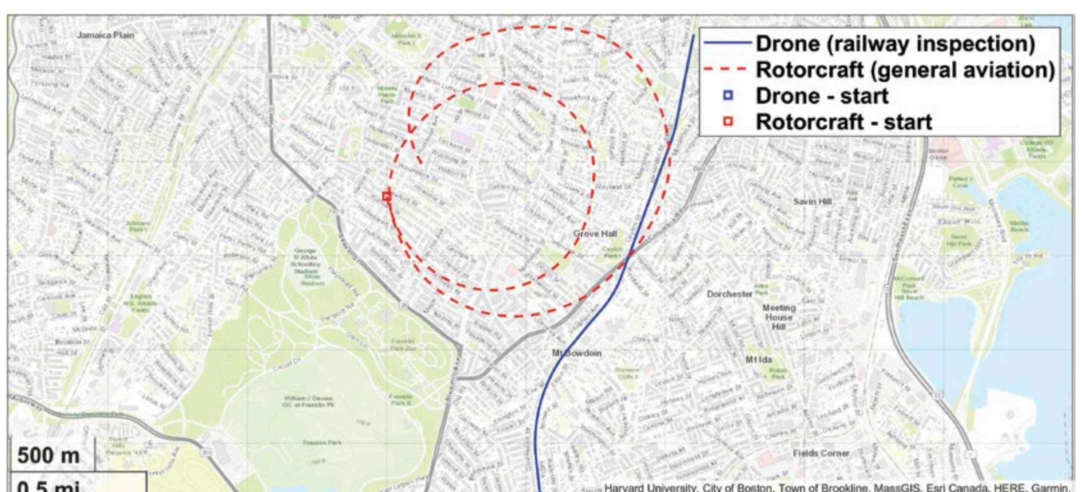


Shown at left is the layout of select Common Evaluation Platform components built for a Xilinx VC707 field-programmable gate array (FPGA) development board.

The Common Evaluation Platform (CEP) provides an extensive, open-source, hardware-verification environment for system-on-a-chip security. CEP allows the Department of Defense, in partnership with industry and academia, to design and test security mechanisms to prevent, deter, or detect realistic hardware threats, including malicious functionality hidden within microelectronic designs.

Airspace encounter models have been distributed via open source and are in use by NASA, the Federal Aviation Administration (FAA), and industry. This suite of statistical models, datasets, and algorithms was primarily developed by Lincoln Laboratory, with contributions from the Stanford Intelligent Systems Laboratory and the FAA Center of Excellence for Unmanned Aircraft Systems (UAS). The suite provides a safety assessment framework for developing small and large UAS restrictions and requirements for safe flight in the national airspace.

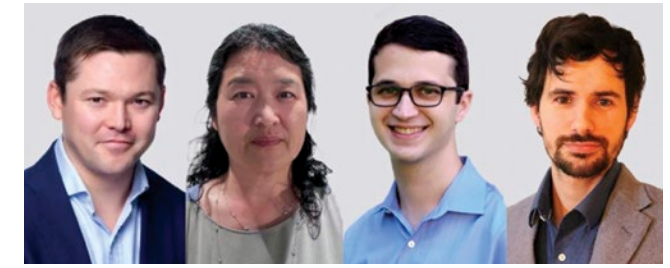
The open-source software project Try-Once Real-Time Software Transactional Memory (STM), or TORTIS, has been distributed as the first, retry-free memory synchronization approach for multicore, safety-critical systems. TORTIS helps improve complex, concurrent, multithreaded task scheduling central to autonomous vehicles, networked medical devices, and smart grids. A companion article won an outstanding paper award at the Real-Time Systems Symposium, a leading IEEE conference.



Lincoln Laboratory's advanced encounter models simulate aircraft behavior and are used to make flying safer for manned and unmanned aircraft. At left is a screenshot from an encounter model.

Outreach and Entrepreneurial Education Efforts

There is a growing recognition within the government and the defense innovation community in general that the private investment engine driving the U.S. economy has not adequately focused on "tough tech"—the typically hardware-based, high-risk/high-payoff technology development that requires years of nurturing, expensive and/or specialized equipment, and a high degree of subject-matter expertise. As one means of addressing this problem, Lincoln Laboratory, in partnership with Lawrence Berkeley National Laboratory, supported its second cohort of entrepreneurial research fellows in a multiyear program that incubates new companies focused on advanced electronics development. The Defense Advanced Research Projects Agency funds the fellows, and the fellowships are administered by the nonprofit organization Activate. Each fellow embeds for a period of two years at the Laboratory and has access to unique facilities and resources and extensive technical and entrepreneurial mentorship.



The 2021 Activate Fellows (with their companies' names) are, from left to right, Brendan Hermalyn (Pythagorean Applied Research), Jungah Lee (Aura Intelligent Systems), Andrew Stern (Coremeleon), and Mael Flament (Qunnect).

Above, Keylime, the Linux-based open-source zero-trust architecture, continues to grow in adoption with an FY21 roll out to IBM's entire cloud fleet. The Forensic Video Exploitation and Analysis is a suite of analytic tools that makes it easier for investigators to review surveillance video footage. Shown at right is a portion of the system's interface.

The TVO has undertaken a wealth of activities designed to promote entrepreneurial education among Laboratory staff members. These efforts are geared toward teaching what it means to create transferable technology, how customer needs influence research goals, and what the real-world challenges inherent in starting a new tech-focused company are. Custom online learning opportunities and MIT's Innovation Corps (I-Corps) Spark serve as flagship staff education platforms. More than 115 Laboratory staff members have now graduated from the I-Corps program.

It is equally important that others learn of the capabilities being developed at the Laboratory, and Laboratory staff members participated in multiple events whose objectives were to expose the external community to technology transfer and collaborative research opportunities. In FY21, these events included CyberWeek, Innovation Studio's Venture Café, and MIT Industrial Liaison Program's topical R&D webinars. At these events, technical staff gave "lightning talks" on technologies such as free-space laser communication, artificial intelligence, DNA forensics, resilient safety-critical systems, lightweight antenna arrays, and aviation technology. Finally, two Laboratory technologies—Forensic Video Exploitation and Analysis, and Keylime—earned Northeast Regional Federal Lab Consortium awards for excellence in technology transfer.

Looking Ahead

The TVO continues to ensure that the Laboratory's government sponsors and their partners have access to available technologies developed at the Laboratory. Recognizing that commercialization also serves the government's interests, the TVO will expand its focus on attracting licensees and creating a robust licensing pipeline. The TVO expects to grow its entrepreneurial fellowship opportunities and is in the early planning stages of developing an off-site office/lab presence designed for staff engagements with startups in the national security sector. The TVO will also continue to grow its intellectual property portfolio, including non-software copyrightable works and open-source software. The TVO aims to expand educational efforts for the FFRDC/UARC community and Laboratory sponsors, and will continue to consult with peer organizations so that everyone can benefit from the lessons learned. Finally, in support of the standup of a dedicated Climate Change Initiative at the Laboratory, the TVO will focus on nonfederal opportunities—including with nonprofits and the commercial sector—to help address critical adaptation, mitigation, and sustainment strategies related to climate change.

>> *Technology Transfer, cont.*

U.S. Patents Granted to Lincoln Laboratory Inventors, 1 October 2020–30 September 2021

Wide Field of View Narrowband Imaging Filter Technology
U.S. Patent 10,794,819; issued 6 October 2020

Methods and Apparatus for Photonic-Enabled Radio-Frequency (RF) Cancellation
U.S. Patent 10,812,118; issued 20 October 2020

Systems and Methods for Detecting Objects in Underwater Environments
U.S. Patent 10,809,376; issued 20 October 2020

System and Method for Cyber Sensing for Power Outage Detection
U.S. Patent 10,812,351; issued 20 October 2020

Systems and Methods for Quantitative Assessment of a Computer Defense Technique
U.S. Patent 10,819,752; issued 27 October 2020

Substrate Containing Latent Vaporization Reagents
U.S. Patent 10,816,530; issued 27 October 2020

Multipolarized Vector Sensor Array Antenna System for Radio Astronomy Applications
U.S. Patent 10,826,199; issued 3 November 2020

Semiconductor Surface Passivation
U.S. Patent 10,825,950; issued 3 November 2020

Dual Polarized Notch Antenna Having Low Profile Stripline Feed
U.S. Patent 10,833,423; issued 10 November 2020

Integrated Circuit (IC) Portholes and Related Techniques
U.S. Patent 10,839,109; issued 17 November 2020

Toroidal Propeller
U.S. Patent 10,836,466; issued 17 November 2020

System and Method for Analyzing Tissue Using Shear Waves
U.S. Patent 10,835,202; issued 17 November 2020

Droplet Heat Exchange Systems and Methods
U.S. Patent 10,852,078; issued 1 December 2020

Block Copolymer Ink Formulation for 3D Printing and Method of Making a 3D Printed Radiofrequency (RF) Device
U.S. Patent 10,851,251; issued 1 December 2020

Lidar Resistant to Interference and Hacking
U.S. Patent 10,852,433; issued 1 December 2020

Focal Plane Array Processing Method and Apparatus
U.S. Patent 10,893,226; issued 12 January 2021

Multi-Spatial Mode Enabled PAT and AO Terminal Architecture for Free-Space Optical Communications
U.S. Patent 10,892,824; issued 12 January 2021

Thermal Management of RF Devices Using Embedded Microjet Arrays
U.S. Patent 10,903,141; issued 26 January 2021

Electro-optic Beam Controller and Method
U.S. Patent 10,901,240; issued 26 January 2021

Computational Reconfigurable Imaging Spectrometer
U.S. Patent 10,909,670; issued 2 February 2021

Inflatable Reflector Antenna and Related Methods
U.S. Patent 10,916,859; issued 9 February 2021

Dual-Mode Imaging Receiver
U.S. Patent 10, 931,372; issued 23 February 2021

Systems, Apparatus, and Methods Related to Modeling, Monitoring, and/or Managing Metabolism
U.S. Patent 10,925,513; issued 23 February 2021

Surface Penetrating Radar and Battery Systems
U.S. Patent 10,935,655; issued 2 March 2021

Spectrally Efficient Digital Logic (SEDL) Analog to Digital Converter (ADC)
U.S. Patent 10,944,415; issued 9 March 2021

Physical-Layer Quantum Error Suppression for Superconducting Qubits in Quantum Computation and Optimization
U.S. Patent 10,942,804; issued 9 March 2021

Foam Radiator
U.S. Patent 10,950,929; issued 16 March 2021

System and Technique for Mitigation of Clutter in Radar
U.S. Patent 10,955,524; issued 23 March 2021

Microwave Resonator Readout of an Ensemble Solid State Spin Sensor
U.S. Patent 10,962,611; issued 30 March 2021

Radiometer Systems and Methods
U.S. Patent 10,983,245; issued 20 April 2021

Targeted Ratio of Signal Power to Interference Plus Noise Power for Enhancement of a Multi-User Detection Receiver
U.S. Patent 11,005,507; issued 11 May 2021

Modular Microjet Cooling of Packaged Electronic Components
U.S. Patent 11,018,077; issued 25 May 2021

Optical Modulator RF Electrodes
U.S. Patent 11,016,360; issued 25 May 2021

Systems and Methods for Composable Analytics
U.S. Patent 11,023,105; issued 1 June 2021

Systems and Methods for Risk Rating of Vulnerabilities
U.S. Patent 11,036,865; issued 15 June 2021

Chopped Bias Magnetic Field Solid-State Spin Sensor for Low Frequency Measurements for Physical Quantities
U.S. Patent 11,041,916; issued 22 June 2021

Method and Apparatus for On-Chip Per-Pixel Pseudo-Random Time Coded Exposure
U.S. Patent 11,050,963; issued 29 June 2021

Methods and Apparatus for Deployable Sparse-Aperture Telescopes
U.S. Patent 11,048,062; issued 29 June 2021

Narrow-Linewidth Microcavity Brillouin Laser with Suppressed Temperature Fluctuations
U.S. Patent 11,048,062; issued 29 June 2021

Inhalable Nanosensors with Volatile Reporters and Uses Thereof
U.S. Patent 11,054,428; issued 6 July 2021

Methods and Apparatus for Acoustic Laser Communications
U.S. Patent 11,082,127; issued 3 August 2021

Single-Frequency Fiber Amplifier with Distal Cladding Stripper
U.S. Patent 11,108,209; issued 31 August 2021

Apparatus, Systems, and Methods for Nonblocking Optical Switching
U.S. Patent 11,112,564; issued 7 September 2021

Methods and Apparatus for Three-Dimensional (3D) Imaging
U.S. Patent 11,112,503; issued 7 September 2021

System and Technique for Loading Classical Data into a Quantum Computer
U.S. Patent 11,113,621; issued 7 September 2021

Compact Cavity-Backed Discone Array
U.S. Patent 11,121,473; issued 14 September 2021

Efficient Operations

In 2021, Lincoln Laboratory continued to simplify processes, build new capabilities, and modernize technology to enable employees to excel in the business of research. Upgrades to information services continued to support employees working remotely amid the COVID-19 pandemic. Progress continued on the Laboratory's multiyear Digital Enterprise Transformation initiative.

The Digital Enterprise Transformation program aims to streamline processes across the Laboratory. At left, C. Scott Anderson, Assistant Director for Operations, shares a presentation about the program's guiding principles of focusing on the enterprise, sharing knowledge, designing for the customer, cultivating strategic thinking, and empowering employees.

Enhancing Information Technology and Services

The Information Services Department (ISD) led and completed several key initiatives in 2021:

- Health and safety applications. ISD collaborated with Laboratory departments to roll out a COVID-symptom reporting kiosk, streamline manual health reporting for visitors, and aid the Laboratory's vaccination reporting program. A modified paid family medical leave process was implemented.

- Information technology enhancements. Laboratory email and personal data were migrated to the cloud, setting the stage to leverage the full power of integrated, cloud-based systems. ISD also migrated applications that were based on Adobe Flash to newer platforms. New online tools are simplifying the purchase of Laboratory equipment and streamlining the reporting and tracking of Laboratory projects.

- Security for information technology. ISD initiated several important security enhancements in 2021, including the deployment of a streamlined endpoint-management program. New vulnerability management dashboards were implemented, and a new enterprise collateral network was built and rolled out. ISD also offered new platforms that helped enhance existing applications and continued SAP analytics and cloud implementations.

- Upgraded website capabilities. The Laboratory's intranet homepage received key upgrades, including a new event-management system. ISD also refreshed or created websites for several Laboratory groups and offices, such as the Flight Test Facility and Office of Diversity and Inclusion, and created the Laboratory's 70th Anniversary website.

- Workforce management improvements. ISD was instrumental in rolling out a new workforce management application, SAP Fieldglass, and in gaining the Laboratory's Contingent Worker Distribution Certification. A new-badge request application was also streamlined. In support of the Laboratory's diversity and inclusion principles, ISD enabled the ability for employees to display their preferred name on Laboratory communication platforms and business applications.

- Infrastructure augmentations. Rollouts of infrastructure-as-a-service and storage-as-a-service were completed. In addition, remote Laboratory sites were migrated to a less expensive internet network.

- Assistance for other Laboratory entities. ISD continues to collaborate on projects across the Laboratory, playing instrumental roles in such projects as warehouse management, special programs reporting, and research programs, including a multidomain radar system.

Transforming the Digital Enterprise

Lincoln Laboratory is modernizing the way it works as part of the Digital Enterprise Transformation (DET). The Business Transformation Office (BTO) continues to lead this multiyear initiative to achieve five main objectives:

1. Advance a culture of ownership, accountability, and deliberate continuous improvement

2. Enable the workforce with new capabilities aligned with a digitally mature organization

3. Simplify and improve core business processes

4. Inform decisions with data-driven insights, and rely on metrics and key performance indicators to identify challenges and successes

5. Utilize integrated technology solutions

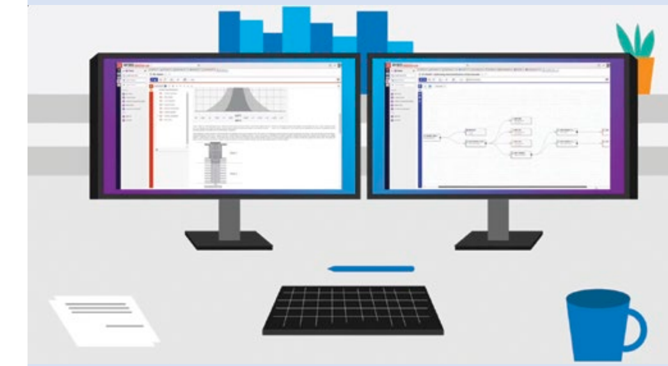
In 2021, the BTO partnered with department heads and project owners to make progress on several DET initiatives:

- Finance modernization and SAP S/4. Phase 1 of this initiative, led by the Financial Services Department, is focused on delivering one trusted financial source and a scalable business platform to drive decision-making and direction setting for the Laboratory. In 2021, the critical design review was completed; S/4 functionality was implemented; and testing, training, and communications were initiated for going live in April 2022.

- External workforce services (EWS) and SAP Fieldglass. Since March 2021, the EWS team has been providing full-service support for hiring managers and managing supplier relationships and performance. The EWS team, with the Contracting Services Department (CSD), also launched SAP Fieldglass. This application automates the end-to-end external labor hiring process, allows visibility between suppliers and workers, provides alerts and dashboard reporting, and has mobile capability. Improvements due to EWS and SAP Fieldglass include the following:
  - ✓ Reduced duplication of efforts
  - ✓ Increased supplier accountability for their performance
  - ✓ Earlier initiation and tracking of subprocesses
  - ✓ Reduced administrative burden
  - ✓ Faster cycle times from job posting distribution to offer

- Continuous improvement. The BTO is establishing a framework for continuous improvement in support of the DET. As part of this effort, the BTO is hosting workshops to guide process owners through the business process management framework. These workshops have already yielded results:
  - ✓ CSD reported a time savings of 10% in the steps of their shipping process, and eliminated paper by moving to electronic solutions.
  - ✓ The Human Resources Department removed a major source of waste by implementing a fax-to-email-inbox capability.

Digital Engineering Center



Digital engineering enables organizations to solve complex problems accurately and efficiently. The U.S. government is increasingly recognizing the importance of digital engineering for developing next-generation national security systems. In response, the Laboratory established the Digital Engineering Center to improve prototyping capabilities, conduct research in digital engineering, and serve as a resource for the government. A main focus is on leveraging a platform called Innovator, which connects all of a program's information, from models and specifications to decision points and data, together in one system. In addition, a mentorship program will help employees understand how digital engineering can benefit their particular job functions and programs.

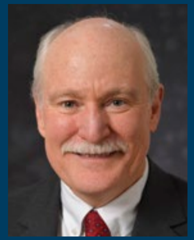
MISSION AREAS

This laser communications (lasercom) ground terminal transmits data back and forth between the Earth's surface and satellites in geostationary orbit. Laboratory engineers designed both the ground and space terminals for this lasercom system.

Space Security

Ensuring the resilience of the nation's space enterprise by designing, prototyping, operating, and assessing systems to provide space domain awareness, resilient space capability delivery, active defense, and associated cross-domain battle management

Leadership



Dr. Grant H. Stokes
Division Head

Mr. D. Marshall Brenizer
Assoc. Division Head

Dr. Gregory D. Berthiaume
Asst. Division Head

Mr. Lawrence M. Candell
Asst. Division Head

Researchers prepare one of the two Situational Awareness Camera Hosted Instruments (SACHI) for thermal vacuum testing. Each SACHI payload measures 45 × 31 × 19 inches and weighs 154 pounds.

Principal 2021 Accomplishments

- The Space Surveillance Telescope (SST), relocated to the Naval Communication Station Harold E. Holt in Australia, completed the Australian demonstration testing. The SST will begin U.S. Space Force Operational Acceptance Testing in anticipation of becoming operational as part of the Operational Space Surveillance Network in 2022.

- The Situational Awareness Camera Hosted Instrument (SACHI) program is developing two identical hosted-payload space domain awareness sensors. SACHI leverages ORS-5 (SensorSat) technologies to provide a rapid development and delivery sensor system that has significant onboard space situational awareness data processing capabilities. SACHI successfully completed assembly and testing of the engineering development unit, and researchers are now assembling and testing the two hosted-payload sensors. The two flight units will be delivered to Japan for satellite integration in 2023.

- A portfolio of activities continues to deliver critical space domain awareness information and tools to the National Space Defense Center in Colorado and the Combined Space Operations Center in California. The Laboratory is leading the modernization of networking, data architecture, and processing capabilities of legacy space surveillance sensors to improve the timeliness of tactical missions. Laboratory-built prototypes of net-centric data libraries have enabled a universal data library that allows Space Force operators to leverage commercial space domain awareness data. Laboratory researchers are evaluating commercial data to increase the capacity and diversity of sensors in the network.

- Systems and mission analyses continue to motivate new concepts leveraging advanced technologies at the Space Rapid Capabilities Office, the Space Development Agency, and the Space Enterprise Architect at Space Command. In 2021, several of these concepts were prototyped and tested in the field, with flight programs expected to deliver initial resilient space architectures in 2023.

Future Outlook

Resilience of the nation's space enterprise is a significant national security issue as the reliance of the military on space systems to deliver tactical warfighting effects grows. Improved space domain awareness, and responses on tactical timelines, will be the foundation for increasing the survivability of space systems. Space systems will need to be made fundamentally more resilient to potential adversary actions. The creation of the U.S. Space Force and the re-establishment of U.S. Space Command highlight the growing importance of the space domain.

Major Laboratory focuses are information extraction and integration, and decision support. Developing a net-centric, multidomain architecture, with the agility to discover and incorporate new data sources and services on short timelines, is critical for a warfighting capability that can respond in the time frames required to support space survivability efforts.

TROPICS Pathfinder CubeSat

The TROPICS (Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats) Pathfinder CubeSat was launched into a 525-kilometer polar orbit on June 30, 2021. The Pathfinder space vehicle is the qualification development unit built for the NASA Earth Venture Instrument's TROPICS constellation. Launch and on-orbit demonstration of the vehicle is a risk-reduction flight test ahead of the full TROPICS constellation launch, scheduled for early 2022. TROPICS CubeSats contain advanced compact microwave sounders that provide high-revisit observations of precipitation, temperature, and humidity in tropical storms. At right, a Laboratory staff member makes final adjustments to the flight vehicle prior to pre-launch testing.

Air, Missile, and Maritime Defense Technology

Investigating system architectures, prototyping pathfinder systems, and demonstrating these advanced, integrated sensor systems that are designed for use on maritime and airborne platforms to provide defense against missiles and other threats

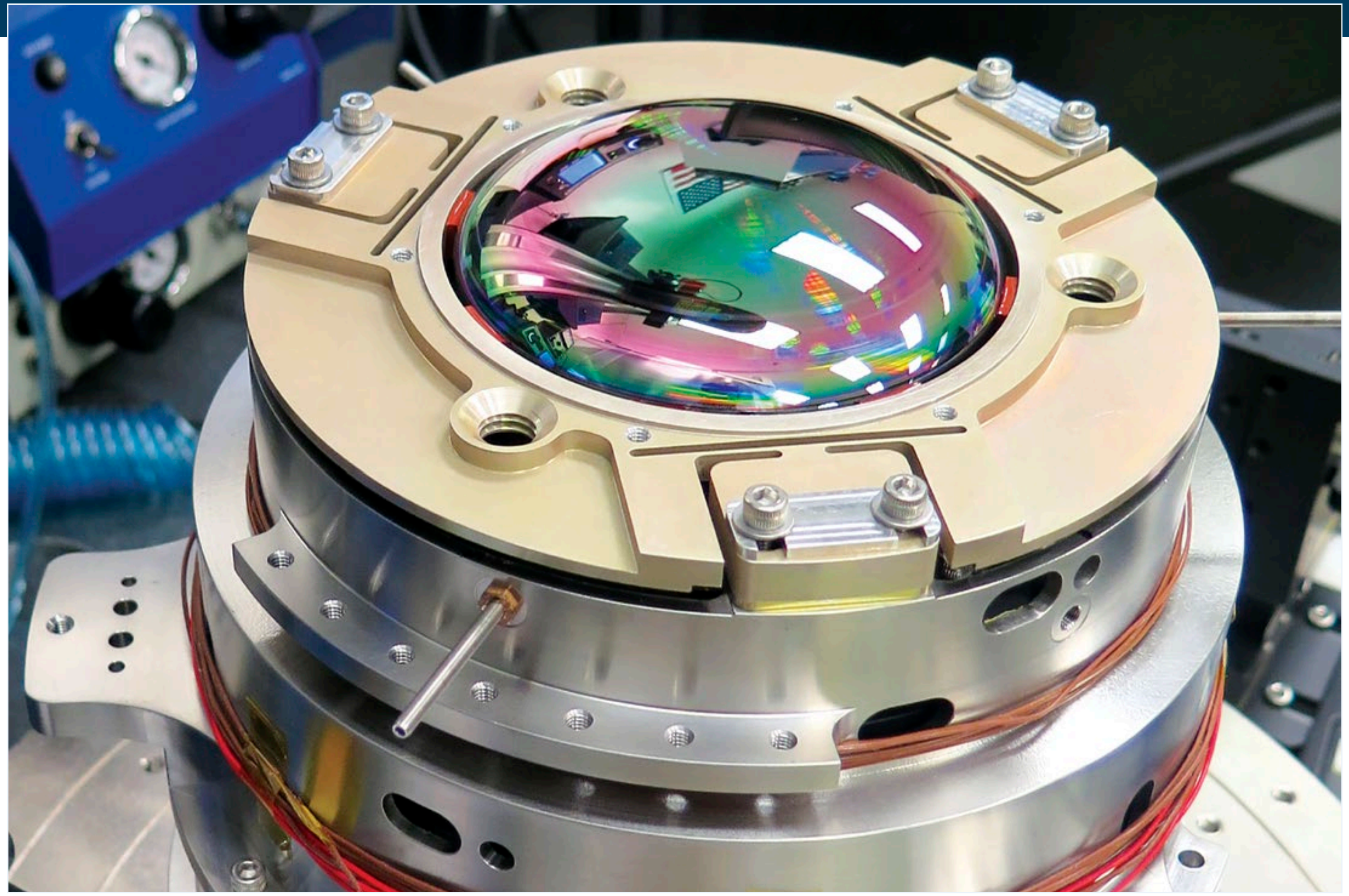
Leadership

Dr. Katherine A. Rink
Division Head

Dr. William J. Donnelly III
Asst. Division Head

Dr. Aryeh Feder
Asst. Division Head

Heidi C. Perry
Asst. Division Head



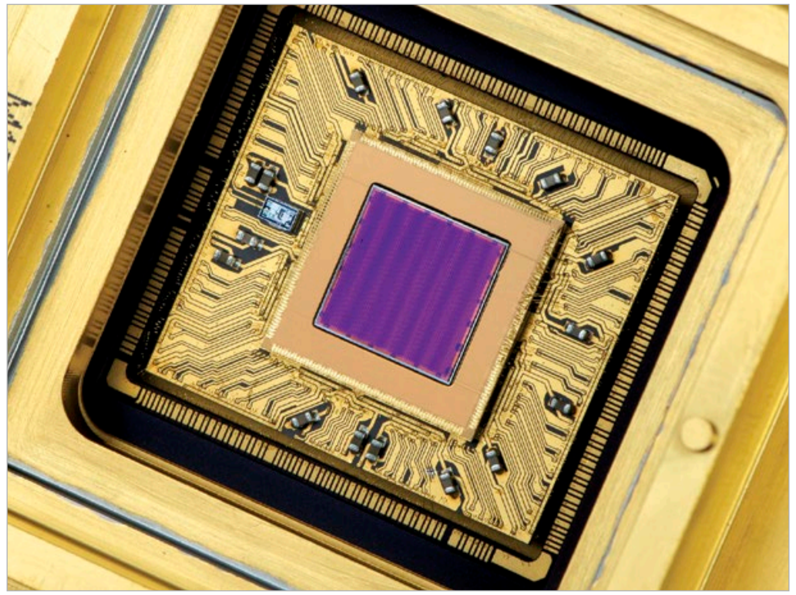
Lincoln Laboratory co-received the Innovation Team Award from the Missile Defense Agency for developing an extremely wide field-of-view sensor. A prototype was transitioned to the U.S. Army Aviation and Missile Center for testing as a government reference sensor for future space programs.

Principal 2021 Accomplishments

- The Laboratory supported a Missile Defense Agency (MDA) study to define an effective and survivable architecture for defending Guam against advanced threats in the Pacific theater.
- Sponsored by the Air Force Life Cycle Management Center Digital Directorate, the Laboratory is studying system requirements, evaluating operational site locations, and developing preliminary technical designs for advanced high-frequency over-the-horizon radar systems for homeland defense.
- The Laboratory is applying its artificial intelligence (AI) systems expertise to Missile Defense System threat discrimination and establishing AI robustness as a key performance metric.
- To enhance U.S. undersea warfare capability performance, the Laboratory has been developing improved sensing architectures, electronic warfare techniques, and signal processing capabilities. The Laboratory has also been exploring new integrated approaches leveraging AI and machine learning to display, label, and classify sonar data.
- In support of the Office of Naval Research, the Laboratory continued developing and testing a distributed multidomain radar capability and advanced signal processing techniques for eventual use by forward-deployed forces.
- The Laboratory developed an ocean state estimation system to provide nowcasts of temperature, salinity, and currents to undersea vehicles. The nowcasts are computed on a single-board computer by combining a reduced-order model with measurements from onboard sensors. The system will be deployed in ocean gliders later this year for a demonstration.
- Radar data were collected along the California coast to validate advanced clutter-mitigation algorithms—which separate slow-moving targets of interest from the sea surface—for radar maritime surveillance.
- A low-cost localization system with custom distributed, adaptable-response transponders for communications-constrained environments like building interiors was prototyped and demonstrated.

Radiation-Tolerant Focal Planes

The U.S. government's interest in proliferated constellations of small imaging satellites is driving a need for radiation-tolerant focal plane technologies. The Laboratory designed, fabricated, and packaged hybridized digital electro-optical and infrared focal planes (like the array pictured at right) and tested device performance in representative radiation environments. The results provided insights into the optimum design of radiation-tolerant high-performance focal planes.



Future Outlook

Hypersonics pose an emerging threat to the United States and its allies. Lincoln Laboratory is working with the MDA to define a defense architecture and develop advanced technologies to counter such threats.

The Laboratory will continue system analysis and advanced concept development to ensure U.S. dominance in the undersea domain. The focus on enabling technologies for unmanned undersea vehicles includes research and development in advanced sensors, high-capacity energy systems, and autonomy-facilitating algorithms.

To deter aggression in regional conflicts, forward-deployed forces may benefit from longer-range, cross-domain engagement webs enabled by new sensing and engagement paradigms. The Laboratory is defining distributed architectures and developing sensor prototypes to support these engagements.

Communication Systems

Advancing communication capabilities for national security and space exploration through technology development in satellite communications, robust networking, laser communications, quantum systems, and agile spectrum operations

Leadership

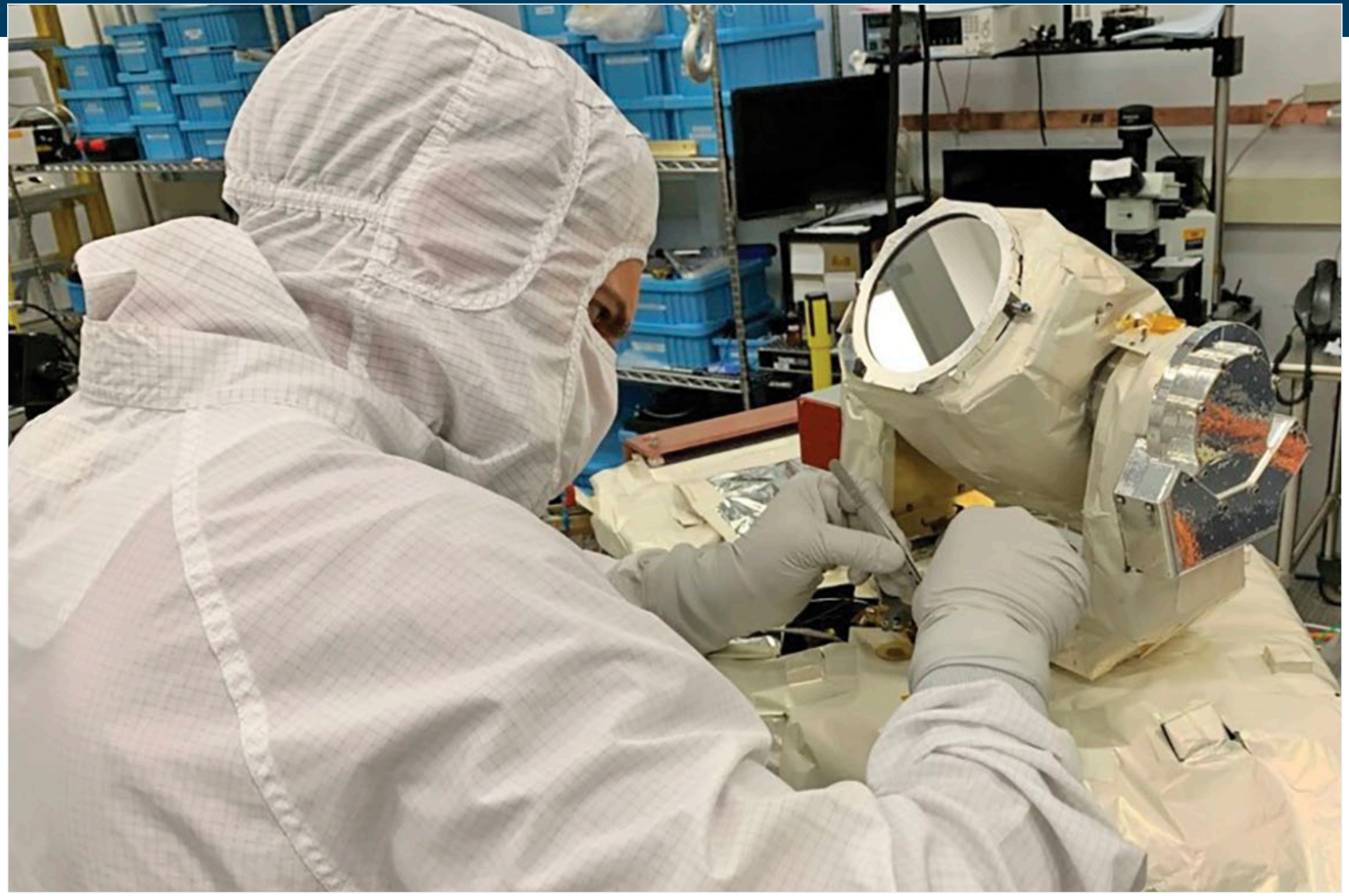
Dr. J. Scott Stadler
Division Head

Dr. James Ward
Assoc. Division Head

Dr. Thomas G. Macdonald
Asst. Division Head

Dr. Don M. Boroson
Laboratory Fellow

Dr. Gary F. Hatke
Principal Staff



The Laboratory is working closely with industry to develop two high-rate laser communication terminals for use in space. One terminal, shown here being prepared for thermal-vacuum testing, will be flown on the NASA Artemis II mission, and the other will be deployed on the International Space Station.

Principal 2021 Accomplishments

- Lincoln Laboratory successfully conducted airborne demonstrations of scalable, resilient, line-of-sight networking techniques that enable Department of Defense platforms to reliably connect and share data.
- Partnering with several government laboratories, the Laboratory experimented with network topologies for long-range, high-frequency links. High-frequency networks can provide beyond-line-of-sight communications through ionospheric refraction without the need for satellites.
- The Laboratory demonstrated a prototype of a new communications capability that leverages airborne multifunction apertures to communicate to multiple users on low–size, weight, and power platforms.
- The Laboratory developed a novel pump-forwarding architecture for synchronization within quantum networks. The approach was validated by using a 3.2-kilometer free-space link.
- A prototype of a new content-aware network architecture to distribute a mission-tailored operational air picture to a ground station was demonstrated at Northern Edge 2021, a U.S. joint field training exercise.
- The Laboratory demonstrated high-rate, blue-green optical communications through the air-water interface at the Field Research Facility pier operated by the U.S. Army Corps of Engineers in Duck, North Carolina.
- Optical receiver architectures that enable coherent processing of optical signals in the digital domain were developed. The approach was used in prototypes of a coherent multiwaveform modem and a system that forms a large aperture from multiple smaller apertures.

Future Outlook

New commercial communications technology, such as 5G, will be evaluated and enhanced to provide cost-effective, reliable communications to the warfighter.

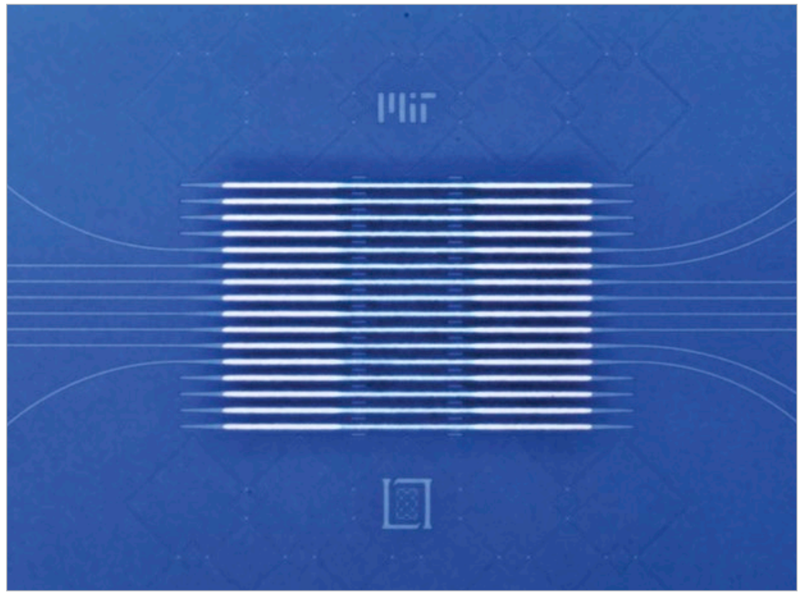
New artificial intelligence approaches to efficiently manage highly dynamic links and networks in dynamic environments will be developed and prototyped.

Working with MIT and Harvard University, the Laboratory will mature architectures and technologies for fiber and free-space quantum networks and integrate them into space and terrestrial experiments.

The Optical Terminal Verification Testbed is an instrumented facility run by an experienced team that provides impartial assessment of laser communication terminal capabilities. The facility will host formal tests of Laboratory, government, and aerospace contractor–developed terminals.

Silicon-Nitride Photonic Integrated Circuit

Lincoln Laboratory is developing an architecture and the component technologies for a scalable quantum network. Shown at right is a silicon-nitride photonic integrated circuit used in quantum memory modules to interface silicon vacancies in diamond-based memories to a fiber network. The chip, designed by Lincoln Laboratory and MIT campus and fabricated at the Laboratory, has a novel through-top oxide socket for memory integration and low-loss edge couplers to connect to optical fibers.



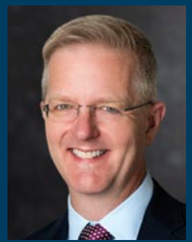
Cyber Security and Information Sciences

Conducting research, development, and evaluation of cyber components and systems, and developing solutions for processing large, high-dimensional datasets acquired from diverse sources, including speech, imagery, text, and network traffic

Leadership

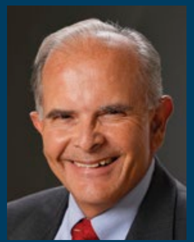
Mr. Stephen B. Rejto
Division Head

Dr. Marc A. Zissman
Assoc. Division Head



Mr. Jeffrey C. Gottschalk
Asst. Division Head

Dr. Jeremy Kepner
Laboratory Fellow



Mr. David R. Martinez
Laboratory Fellow

Researchers working on a Navy project showcased their automated waveform classification prototype at Fort Devens, Massachusetts. The prototype uses generative and discriminative machine learning algorithms to detect and classify RF signals.

Principal 2021 Accomplishments

- The Laboratory produced an initial operational technology to analyze and identify software applications in encrypted network traffic. The system is built on artificial intelligence (AI) advancements made in partnership with MIT's Computer Science and Artificial Intelligence Laboratory.
- The Laboratory continued to develop its cyber-resilient Magnetite operating system layer and demonstrated an application to enable software-based high-assurance cryptography in platforms highly constrained by size, weight, and power needs.
- Researchers continued to advance the state of the art in malware similarity analysis on behalf of the U.S. Cyber Command and other sponsors.
- The Supercomputing Center added 40,000 processing cores and 10 petabytes of storage to sustain its world-leading interactive supercomputing capability.
- An automated cyberthreat intelligence labelling and extraction system was delivered to the Department of Defense. Leveraging advances in natural language processing, the tool is able to label indicators of compromise in unstructured threat reporting.
- The Laboratory supported a Defense Advanced Research Projects Agency (DARPA) program to develop automated machine learning tools that enable subject-matter experts to create state-of-the-art predictive models without the aid of data scientists.
- The Laboratory delivered several versions of its key management system prototype to the Air Force's Space and Missile Systems Center and the prime contractor to serve as a baseline for a live capability.
- The Department of the Air Force Cyber Red Team, in conjunction with the 16th Air Force, conducted adversarial vulnerability assessments of major weapon systems. The assessments led to improvements in system survivability and mission assurance.

Future Outlook

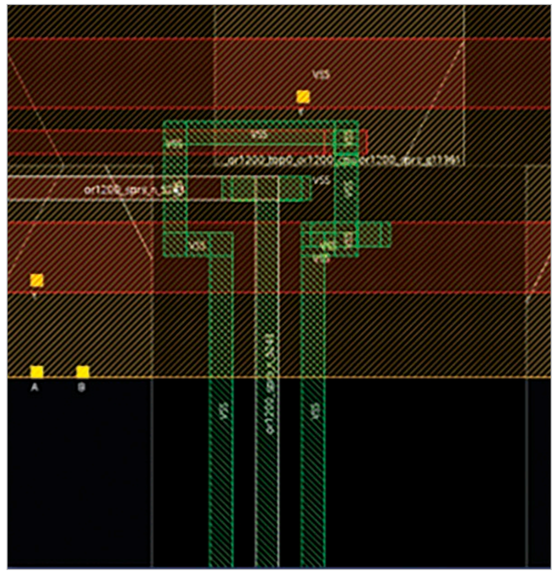
The Laboratory will develop algorithms and a counter-influence operations test bed that will permit the development, demonstration, and assessment of new technology and concepts of operations for detecting and mitigating foreign adversary influence operations.

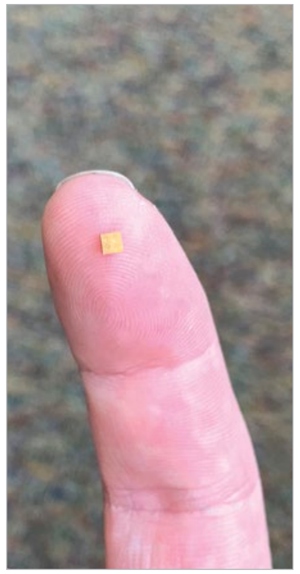
The Laboratory will integrate cyber into all-domain operations (ADO) to provide cyber situational awareness, effects, and defense to advance ADO and to secure data and systems upon which ADO missions depend.

The Resilient Mission Computer team will continue to advance a secure-by-design computer system. A compartmentalized version of the Linux operating system that supports legacy applications is being developed. The team's vision of a foundationally secure computer sparked a new DARPA study.

Defensive Design

To protect against malicious "backdoor" supply-chain attacks, the Laboratory is developing design technologies to secure outsourced integrated circuit fabrication. These technologies include inspection ports and guard wires (shown in green in the left-side photo), which defensively route wires within a design to make malicious modifications both more challenging to achieve and more detectable after fabrication. A demonstration circuit fabricated with these design technologies is shown in the right-side photo. Assuring the integrity of circuit designs that are fabricated in untrusted foundries is a growing national security priority.





ISR Systems and Technology

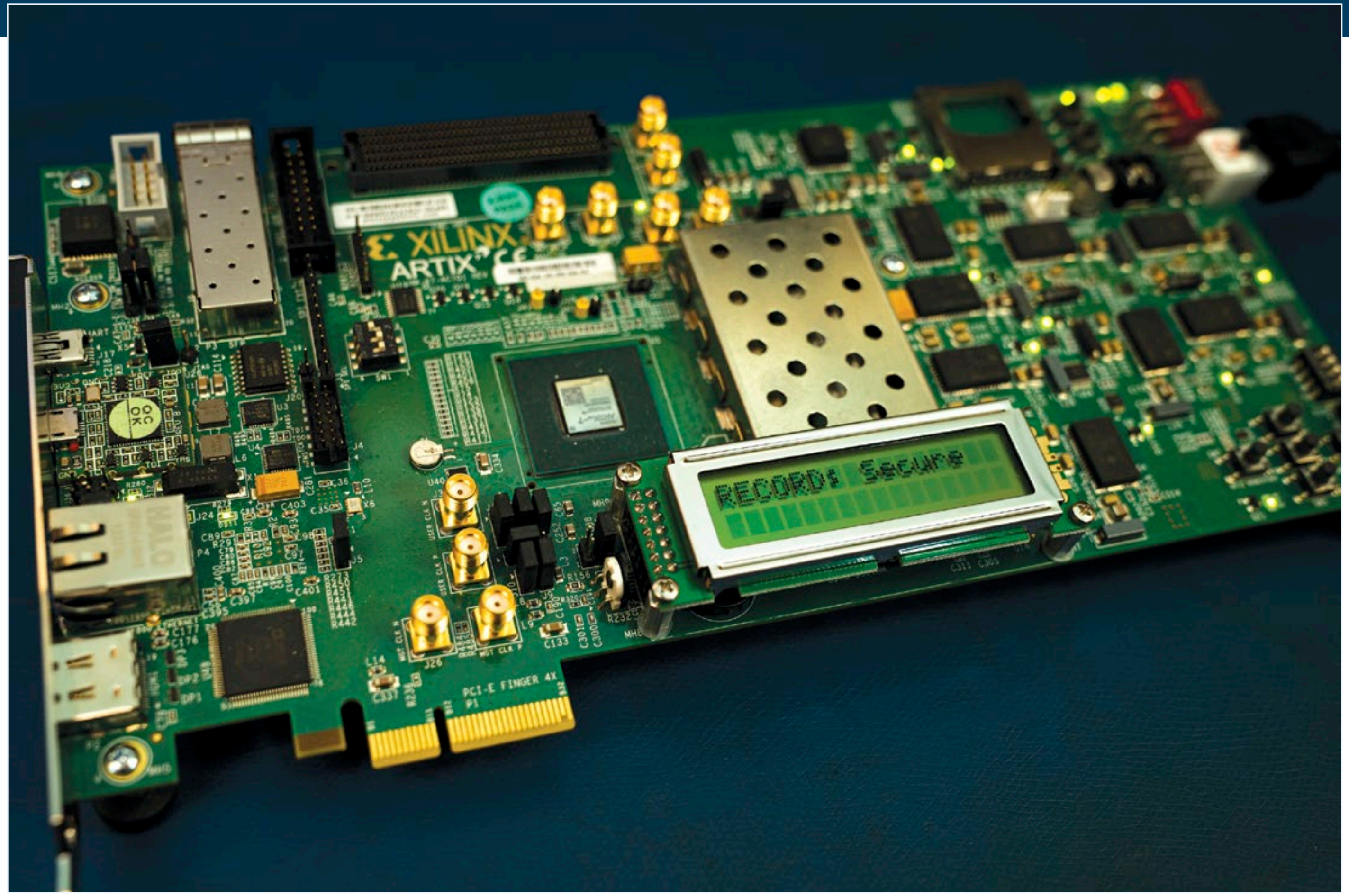
Conducting research and development in advanced sensing, signal and image processing, decision support technology, and high-performance embedded computing to enhance capabilities in intelligence, surveillance, and reconnaissance

Leadership

Dr. Marc N. Viera
Division Head

Dr. Daniel J. Ripin
Asst. Division Head

Dr. Jennifer A. Watson
Asst. Division Head



Through dynamic resource monitoring and allocation, this Laboratory-developed reconfigurable processor enables very low-power, secure edge computing for emerging artificial intelligence and machine learning tasks such as voice and image recognition.

Principal 2021 Accomplishments

- The Laboratory demonstrated a low-power, self-reconfigurable processor with built-in security and trust for machine learning. While still meeting operational requirements, the processor minimizes power consumption by adapting resources depending on the necessary computations.
- The Laboratory led the initial airborne data collection campaign with PHOENIX High CASTLE—an advanced, first-ever zoom-enabled Geiger-mode avalanche photodiode (GmAPD) 3D lidar system—for the U.S. Army Engineer Research and Development Center Geospatial Research Laboratory.
- The Next Generation Sensors program demonstrated a prototype open architecture to enable integrated coherent multisensor signal and artificial intelligence (AI) processing for on-platform tactical-edge scenarios. The associated software development kits will allow third parties to efficiently integrate new mission capabilities.
- The Laboratory continued to remotely enhance capabilities for the premier foliage-penetrating 3D imaging lidar system, Multi-look Airborne Collector for Human Encampment and Terrain Extraction (MACHETE) 2.0, which has completed more than 275 sorties in South America since 2019. AI-based analysis tools were introduced with the aim of expanding our capacity to interpret and utilize imagery.
- The Laboratory pursued techniques to improve the ranging precision of state-of-the-art GmAPD-based lidars. The Laboratory also explored advanced electro-optical and RF detection techniques based on quantum optical effects.
- The Europa Lidar for Situational Awareness program completed design and component verification of a real-time, high-resolution mapping lidar for deep-space landing missions in which sensor mass is extremely limited. Specialized algorithms optimized for embedded computing will enable the system to autonomously provide 10,000 square meters of imagery with a resolution better than 5 centimeters within one second.
- Two versions of the Airborne Radar Testbed were used simultaneously to create a dataset for developing and evaluating bistatic radar modes for ground moving target indication.

Future Outlook

The Laboratory continues to lead the Department of Defense (DoD) community in applying machine learning (ML) to radar. This year, the Laboratory built and tested a polarimetric synthetic aperture radar platform to explore applications of polarimetry to ML, and created and curated a one-of-a-kind dataset of multipolarization signatures of a variety of ground platforms to support ML development across the DoD community.

The Active Optical Systems Group has developed revolutionary lidar and passive sensing systems that have been deployed with great success in semipermissive environments. The group is pivoting toward prototyping active optical systems to operate under challenging circumstances to identify and classify objects of interest in nonpermissive environments. Pioneering disruptive systems for space domain dominance in the DoD and non-DoD arenas will be an additional focus.

Airborne Radar Testbed

The Laboratory's Airborne Radar Testbed (ARTB) has been installed onto its new host aircraft, a Saab-340B (top image). This aircraft can accommodate the size, weight, and power required to integrate ARTB with other sensors systems and a tactical communications system. With these capabilities, ARTB provides the DoD with a low-cost, open-architecture system to test and demonstrate not only new radar technologies (bottom image) but also future multidomain, multisensor concepts of operation.

Tactical Systems

Improving the development of tactical air and counterterrorism systems through systems analysis to assess the impact of technologies on real-world scenarios; rapidly developing prototype systems; and conducting precise instrumented testing of systems

Leadership

Dr. Marc N. Viera
Division Head

Dr. Daniel J. Ripin
Asst. Division Head

Dr. Jennifer A. Watson
Asst. Division Head

Dr. Josh G. Erling
Group Leader

Dr. Janet T. Hallett
Group Leader

An ongoing project with the U.S. Army's Ground Vehicle Systems Center is to pair autonomous ground vehicles, such as the MRZR ATV seen here, with autonomous unmanned aerial vehicles (UAVs), like the Kraken UAV shown in the background, to improve the ATV's off-road navigation.

Principal 2021 Accomplishments

- Lincoln Laboratory researchers continued to conduct systems analyses, laboratory testing, and flight-system data collections that inform assessments of the performance and limitations of Air Force aircraft against current and future threats. These assessments included investigations of missile system performance, electronic attack and electronic protection, and RF and advanced infrared kill chains.

- The Laboratory assessed the Next Generation Air Dominance platform to ensure future U.S. air superiority, focusing on identifying system requirements to counter evolving adversaries in a diverse mission set. These studies combine understanding of adversary capabilities and U.S. technologies to inform future Department of the Air Force acquisition decisions.

- Several studies to improve survivability of U.S. Army forces operating in the United States European Command were completed. The studies inform prototyping of novel camoflauge, concealment, and decoy capabilities, as well as rigorous test and measurement campaigns.

- Analysis efforts expanded to incorporate autonomy and artificial intelligence (AI), including studies of novel teaming concepts for air superiority to support the nation's air defense and examination of adversary implementation of AI approaches to enhance sensing. The Laboratory also continued to examine the impact of air and space integration and joint force operations on air vehicle survivability.

- Researchers developed and demonstrated a grammar-based automatic speech recognition proof of concept in a lab for the Boeing F-15EX platform that enables voice control of an Open Mission Systems–compliant subsystem.

- The Laboratory continues to prototype, test, and transition autonomous systems capabilities that enable operation in challenging and contested environments. Researchers prototyped an unmanned aerial vehicle (UAV) to map a region in front of autonomous ground vehicles (AGVs), allowing them to navigate off road and with real-time navigation assistance. The UAV/AGV team will refine the system's capabilities through future field tests.

Future Outlook

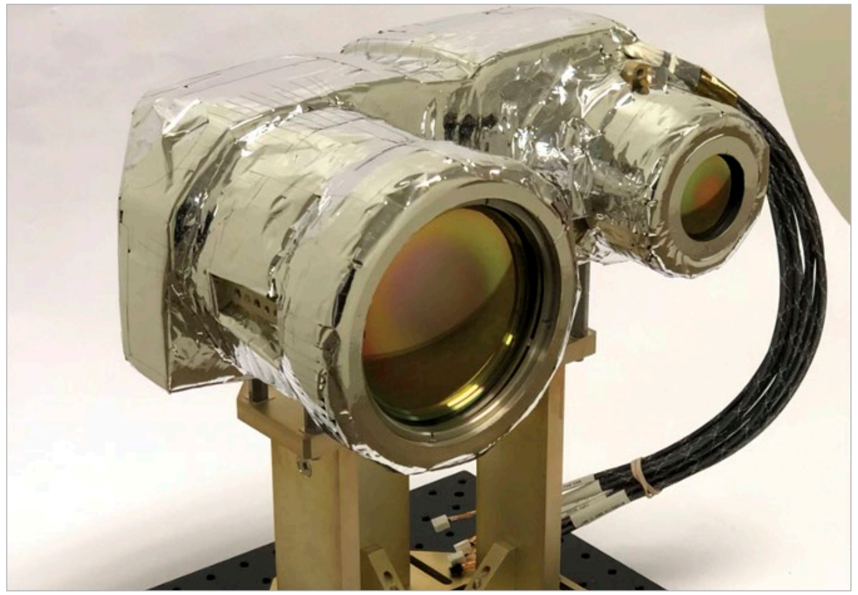
Lincoln Laboratory is increasing focus on U.S. Army maneuver forces and on applying technologies to increase survivability in heavily contested environments. Assessment of peer adversary kill webs will guide prototyping of new camouflage, concealment, and decoy capabilities and their transition to the warfighter.

Work continues on developing autonomous systems capabilities for the warfighter. Future efforts will focus on robust multi-agent teaming algorithms for contested environments, navigation in GPS-denied environments, and novel system-level architectures for unmanned vehicles.

The Laboratory will continue supporting the U.S. Air Force by performing systems analyses, prototyping advanced capabilities, and demonstrating capabilities through measurement campaigns.

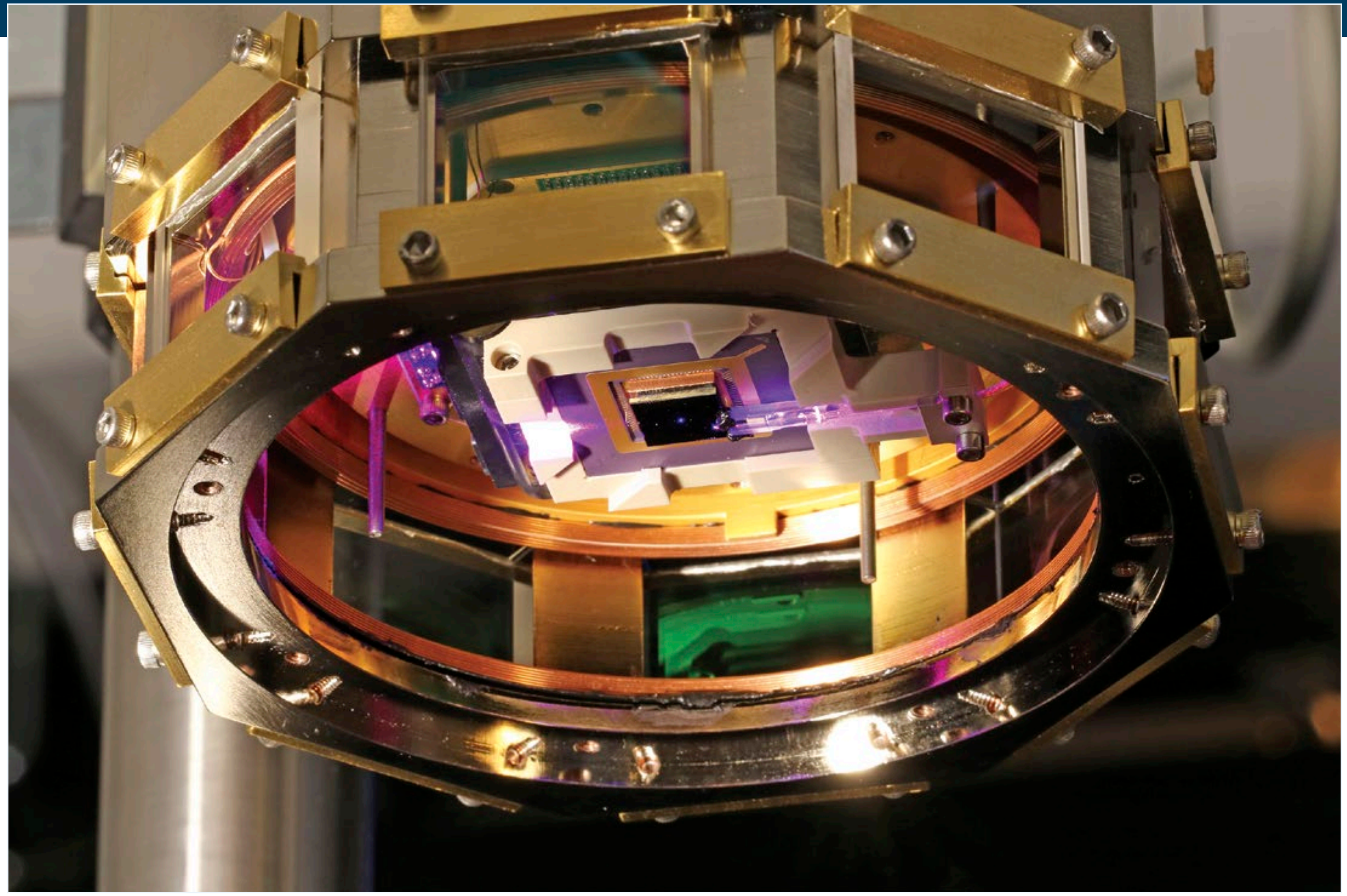
High-performance Infrared Lens for Airborne Radiometry

This custom-designed lens is a key component of a new airborne camera system that accurately measures the brightness of image features in infrared light. The folded configuration of the lens is driven by the space constraints of its mounting location. Infrared light enters the lens through the large aperture on the left and emerges on the right, where an infrared detector array will be positioned. The reflective covering is the outer surface of an insulating blanket that isolates the lens from the temperature extremes encountered during flight.



Advanced Technology

Leveraging solid-state electronic and electro-optical technologies, materials science, advanced RF technology, and quantum information science to develop innovative system applications and components



The Laboratory continues to contribute to the leading edge of quantum computing. The trapped-ion system pictured above achieved the first demonstration of integrating laser signals, needed to control quantum bits (qubits), into a substrate that contains the ion-trap electrodes.

Principal 2021 Accomplishments

- Working collaboratively with the NASA Goddard Space Flight Center, Lincoln Laboratory researchers fabricated a 100,000-pixel X-ray detector array. This array has 1,000 times more pixels than current detectors and is a significant risk-reduction demonstration for future NASA astrophysics applications.

- Progress in quantum computing continues to accelerate. The Laboratory developed a 3D-circuit fabrication approach for realizing complex superconducting qubit circuits. The process will be made available to academic researchers.

- The Laboratory completed a demonstration of the standoff millimeter-wave imager for concealed weapons detection in high-traffic applications, such as subway station screening. The assessment was conducted at the Department of Homeland Security's Maryland Test Facility.

- The Laboratory realized an on-chip, low-noise laser that leverages stimulated Brillouin scattering (SBS) optical gain in an ultralow-loss silicon-nitride waveguide. The measured phase noise of the laser was lower than that of previously reported on-chip SBS lasers.

- In partnership with MIT's Space Propulsion Laboratory and Institute for Soldier Nanotechnologies, researchers developed electrospray thrusters for propulsion of small-scale satellites in space. By using advanced silicon micromachining techniques in the Microelectronics Laboratory, the team increased the emitter density of the thrusters by 10 times compared to the state of the art. Further, the densified thrusters successfully completed ground testing by rotating a magnetically levitated CubeSat in an Earth-bound test environment.

- The Laboratory deployed high-frequency vector sensor instruments to the island of Palau for a study led by the Office of Naval Research. The study is investigating the impact of equatorial anomaly and of spread-F, an ionospheric phenomenon, on radio propagation. From a small-form-factor instrument, the vector sensor can determine the propagation angle and polarization of radio waves.

Leadership

Dr. Robert G. Atkins
Division Head

Dr. Craig L. Keast
Assoc. Division Head

Dr. Mark A. Gouker
Asst. Division Head

Future Outlook

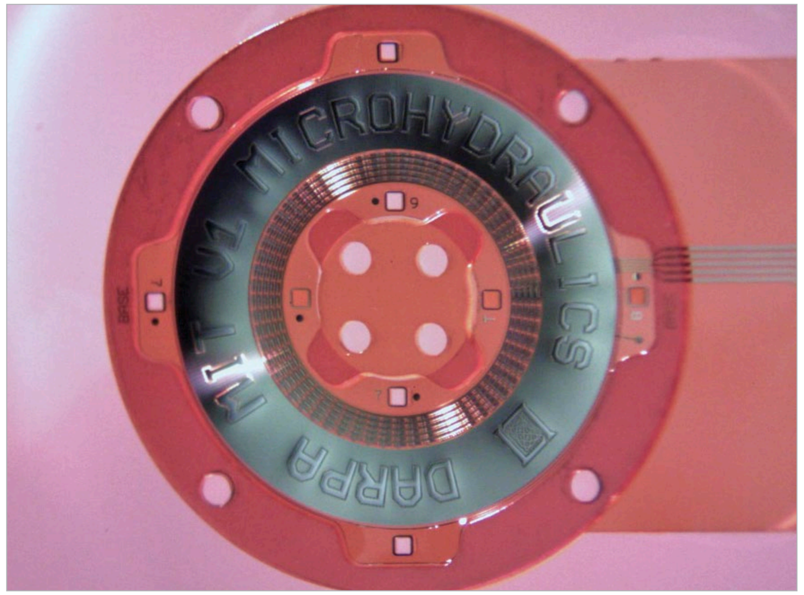
Directed-energy systems using high-energy lasers will be an important addition for Department of Defense (DoD) systems. With the successful demonstration and transition of the Laboratory's fiber amplifier–based systems, work is turning to panel-based approaches using semiconductor laser amplifiers.

Quantum sensing is likely to have impact for DoD applications long before quantum computing does. Field tests and prototype systems for magnetometers, electrometers, and clocks will increase over the next few years.

A resurgence in microelectronics research is focused on keeping the United States' technical advantages in this field. Work is increasing in device technology beyond complementary metal-oxide-semiconductor, next-generation computer architectures, advanced packaging, and microsystems.

Microhydraulic Actuators

The Laboratory developed an electric motor that is based on electrical capacitance actuation. The actuation is achieved via electrowetting, in which surfaces electrically change from hydrophobic to hydrophilic. The motors are constructed by layering polymer sheets with microfabricated electrodes. A pattern of oil and water droplets form between the electrodes, and the sheets move by sequencing voltages on the electrodes, causing alternating hydrophilic and hydrophobic response from the droplets. At right is an image of a prototype motor with a rotor diameter of 6 millimeters and thickness of 200 microns. These motors are especially attractive for small-scale systems needing high mechanical power and efficiency.



Homeland Protection

Innovating technology and architectures to help prevent attacks on the U.S. homeland, to reduce the vulnerability of the nation to terrorism, and to improve the security and resiliency of critical infrastructure, including energy systems, against natural and human-made threats

Leadership

Mr. James M. Flavin
Division Head

Dr. James K. Kuchar
Asst. Division Head

Dr. Chris A.D. Roeser
Asst. Division Head

Lincoln Laboratory developed an airborne edge computing test bed to develop autonomous unmanned aircraft system (UAS) functions for homeland security missions. Above, the team field tested a "chase" UAS that autonomously follows a threat drone back to its point of origin to locate the controller.

Principal 2021 Accomplishments

- To support the Department of Homeland Security Science and Technology Directorate's Screening at Speed vision for improved airport security, the Laboratory developed methods for rapidly assessing image quality and detecting threats within data from body and accessible property scans.
- Energy resilience readiness exercises expanded in scope and impact to include control system cyber impacts to Department of Defense installations. The Laboratory continues transitioning energy resilience technology to outside partners to increase mission readiness.
- The Laboratory continued to develop, deploy, and transition artificial intelligence–enabled decision support systems for maritime, air, and waterway border security applications.
- A highly sensitive radar system was integrated on an unmanned ground vehicle for detection of disaster survivors trapped under rubble. Future plans include integration of this system on an unmanned air vehicle.
- A prototype multisensor air defense system that leverages the Laboratory's expertise in regional air defense was demonstrated in high-profile exercises for the U.S. Air Forces in Europe command.
- A low–size, weight, and power multistatic receiver is being developed to mitigate the impact of wind farms located near joint-use air surveillance systems. A final report was completed on wind farm layout optimization strategies.
- The Laboratory developed and demonstrated an experimental framework and evaluation environment for measuring and building public resilience against hostile foreign influence operations.
- Prototypes employing natural language processing demonstrated new capabilities for identifying potential threat events, characterizing fake-news narratives, and increasing operational agility.
- A video analytics software tool to enhance security operations in critical infrastructure command centers was improved and transitioned to private industry.

Future Outlook

Securing the nation and responding to emerging threats will necessitate new architectures for sensing hostile activities and characterizing environmental conditions. The Laboratory will provide novel sensors leveraging advances in low–cost, size, weight, and power electronics.

Open architectures for leveraging data, applying AI techniques, and providing secure cyber environments in the cloud will enable advanced command-and-control systems for homeland air defense, humanitarian assistance and disaster response, and security of land border and maritime environments.

Critical infrastructure protection and domestic resilience will compel advancements in novel areas beyond sensing and decision support, including cybersecurity, advanced energy, and defense against hostile foreign influence operations.

Novel Multistatic Receivers for Enhancing Air Surveillance

Lincoln Laboratory is developing novel, low-cost receivers to enhance the capabilities of existing air surveillance radar systems. Multiple receivers can be deployed around regions of high-priority airspace to improve sensitivity for small targets, to increase resolution, and to reject ground clutter from wind turbines and other sources. Laboratory researchers are testing custom antennas, as shown in the photo at right, to measure direct-path and reflected signals from current radar systems and are developing real-time multistatic processing algorithms.

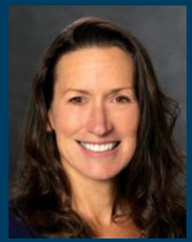
Biotechnology and Human Systems

Advancing technologies and systems for improved chemical and biological defense, human health and performance, responses to the impacts of climate change, and resilience to both natural and human-made disasters

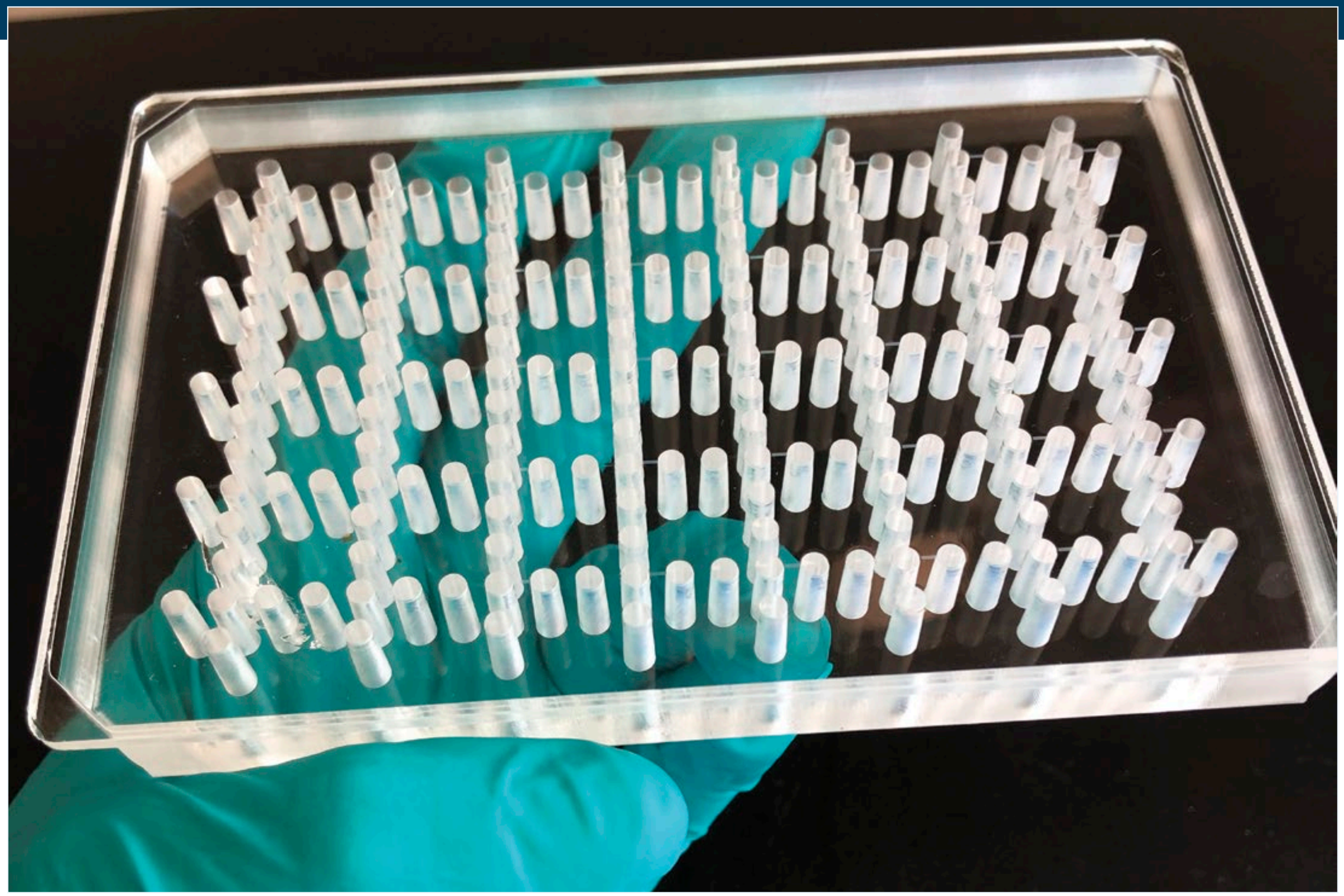
Leadership

Mr. Edward C. Wack
Division Head

Dr. Jeffrey S. Palmer
Asst. Division Head



Dr. Christina M. Rudzinski
Asst. Division Head



Lincoln Laboratory is building organ-on-chip devices to investigate the dynamics of therapeutic or toxic chemicals on human health. Shown here is a microfluidic device that cultures neurophysiologically accurate myelinated motor neurons.

Principal 2021 Accomplishments

- Lincoln Laboratory started developing a decision support architecture and software system to improve the efficiency of international humanitarian assistance through tracking and monitoring of food aid shipments.
- The Laboratory developed novel analytics that automate post-hurricane infrastructure damage assessments from remotely sensed data and prioritize response efforts.
- In response to the COVID-19 pandemic, the Laboratory deployed a national-scale model of demand for personal protective equipment. This model was adapted from one originally built by Laboratory researchers for the state of Massachusetts.
- The Laboratory continued to work with the government to develop and field chemical and biological defense systems, focusing on multiple test beds and data collections in the New York City metropolitan area.
- Lincoln Laboratory is building a cloud-based platform for analyzing physiological data taken from wearable sensors on tens of thousands of participants that will enable novel algorithms for early warning of COVID-19 infection.
- Laboratory staff began building a polymerase chain reaction–based sensor for use on unmanned systems to rapidly and accurately identify biological threats in the environment.
- Lincoln Laboratory prototyped a system for determining whether a person should be evaluated for post-traumatic stress disorder (PTSD) using only their voice. This new capability leverages a novel processing pipeline that captures speech, evaluates the speech signal's quality, and implements a machine learning model. The system will allow care providers with varying levels of expertise to screen for PTSD in clinical settings.
- Laboratory researchers created a semi-automated, large-scale brain mapping system, enabling new opportunities to understand neuronal interactions associated with cognitive functions and disorders. This work uses an active machine learning pipeline and yields improved fidelity and processing speed over previous methods.

Artificial Intelligence–Guided Ultrasound Intervention Device

Future conflicts will require wounded warfighters to be cared for on the battlefield for a day or more before evacuation to a hospital. To save lives, battlefield medics will need to halt massive blood loss by inserting a catheter into a deep blood vessel. Lincoln Laboratory and Massachusetts General Hospital have prototyped and tested a new device, the Artificial Intelligence–Guided Ultrasound Intervention Device (AI-GUIDE), that uses real-time AI and handheld robotics to help guide medics to perform needle insertion on the battlefield. The photo shows AI-GUIDE inserting a needle and guidewire quickly and accurately into a central blood vessel in a vascular access system replica.

Future Outlook

Improving humanitarian assistance, global health, and disaster response activities, as well as reducing the security impacts of global climate change, will motivate work on advanced architectures, sensors, and analytics.

The Laboratory will develop advanced technologies and system architectures for chemical and biological threats, which include pandemics, to protect deployed forces and civilians.

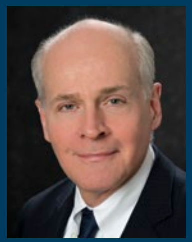
Improving soldier health and performance will require advances in brain-related technologies, physiological sensors, and engineered and synthetic biology.

Artificial intelligence will be leveraged to interpret vast amounts of biological and health data, assist in decision-making, and provide insights for new discoveries.

Air Traffic Control

Developing advanced technologies and decision support architectures for aircraft surveillance, integrated weather sensing and processing, collaborative air traffic management, information security, and optimization to support the nation's air transportation system

Leadership



Mr. James M. Flavin
Division Head

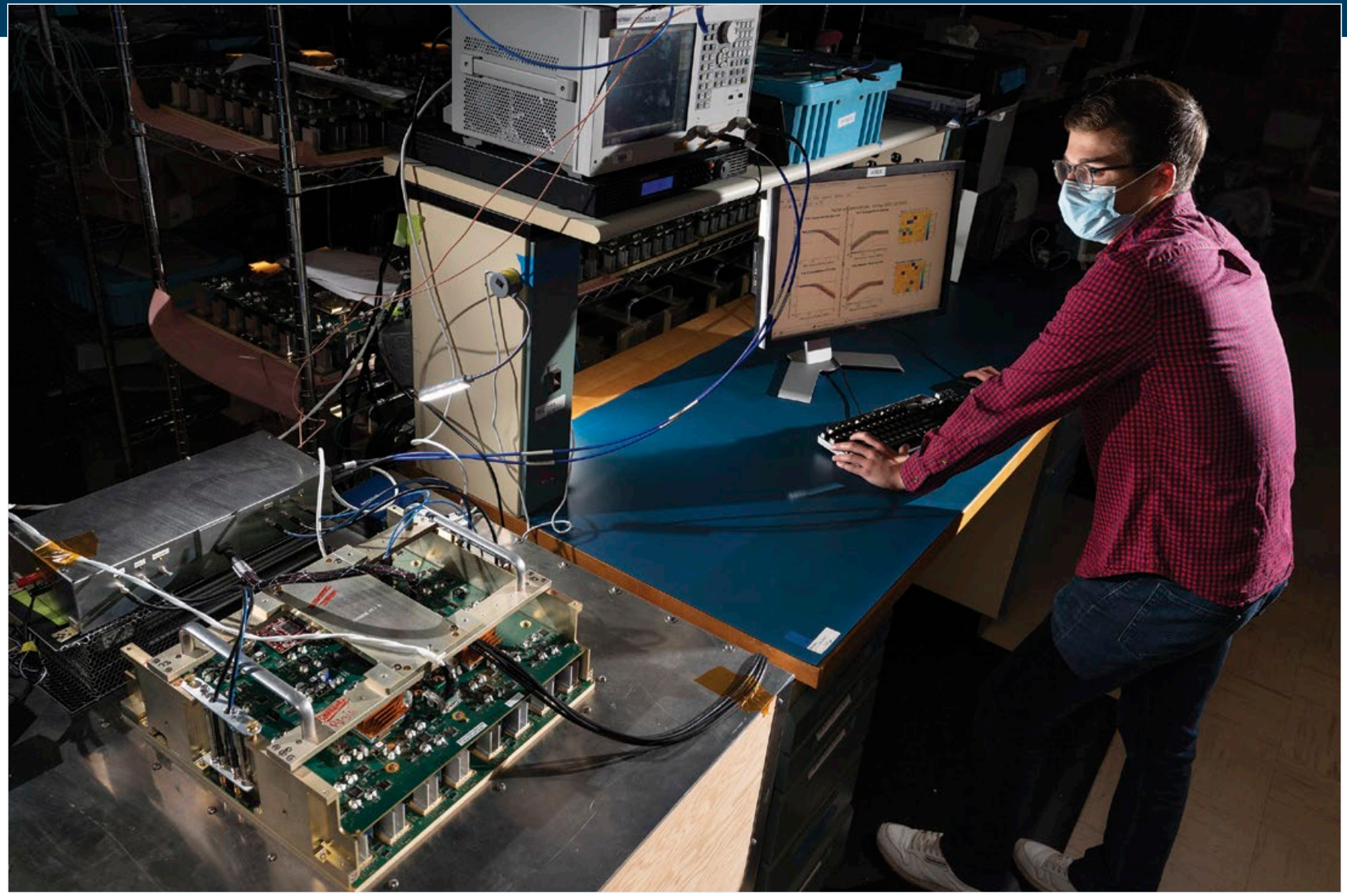
Dr. James K. Kuchar
Asst. Division Head

Dr. Chris A.D. Roeser
Asst. Division Head

Dr. Marilyn M. Wolfson
Laboratory Fellow

Dr. Wesley A. Olson
Group Leader

Dr. Tom G. Reynolds
Group Leader



The Dual-Polarization Phased-Array Radar Advanced Technology Demonstrator (ATD) is a 4-meter array consisting of 76 panels designed to evaluate improvements in rapid-update weather sensing. Here, a team member runs calibration tests on an ATD panel at the Laboratory's RF Systems Test Facility.

Principal 2021 Accomplishments

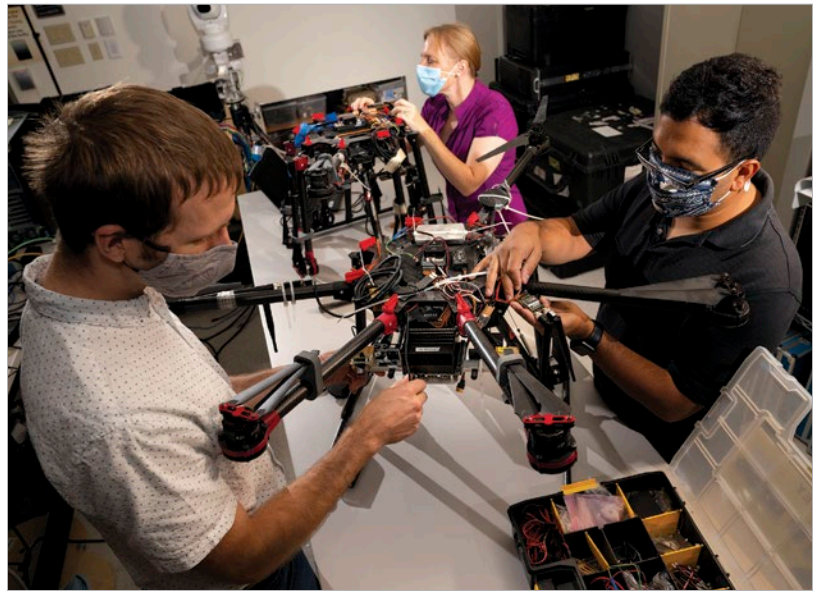
- The Laboratory continued technology transfer of the Small Airport Surveillance Sensor with the Federal Aviation Administration (FAA) and industry partners.
- The Airborne Collision Avoidance System X (ACAS X) for large unmanned aircraft systems (UAS) was finalized and is being incorporated into international standards as it moves toward worldwide deployment. Development of ACAS X for small UAS and rotorcraft continues.
- Operations of the U.S. Navy Triton UAS were conducted using an air traffic separation capability enabled by Laboratory design and safety assessment.
- The Dual-Polarization Phased-Array Radar Advanced Technology Demonstrator finished design verification testing and is now the primary research asset for storm detection and tracking at the National Severe Storms Laboratory in Norman, Oklahoma.
- The Laboratory continued to support FAA Next Generation Weather Systems acquisition, including rapid-update weather radar mosaics and storm prediction technology.
- The Global Synthetic Weather Radar was tested at six U.S. Air Force facilities and is undergoing deployment to a cloud computing environment.
- The Laboratory continued to develop technologies for advanced aviation cyberthreat assessment, detection, and mitigation. A 2021 highlight was the demonstration of an algorithm for the detection of malicious lateral movement within a cloud computing environment.
- The Laboratory continued to develop tools to support mission planning, operational readiness, and force health protection for the U.S. Transportation Command. Recent highlights include a scheduling tool to optimize aerial refueling operations, a cost-estimation model for sealift missions, and a physiological status monitoring capability for the detection of an immunological response to COVID-19.

Future Outlook

The Laboratory will continue to develop future aviation system concepts, including trajectory-based operations, collision avoidance, weather impact mitigation, new entrants (e.g., commercial space, high-altitude operations, and urban air mobility) and environmental impact reduction. Cybersecurity efforts will address potential vulnerabilities in aviation systems. Innovation in weather capabilities will focus on sensing technologies and algorithms for managing airspace capacity. Meteorological surveillance of severe storms will continue to improve, and a next-generation all-digital back end phased array system will be built and deployed. Advanced techniques will be leveraged to forecast weather and system demand and to allocate resources more efficiently and effectively for civilian and Department of Defense transportation applications. The Laboratory will continue to develop standards, safety evaluation methods, and threat-avoidance algorithms.

Airborne Collision Avoidance System X

Under FAA funding, the Laboratory is developing ACAS X algorithms that allow small UAS (sUAS) to detect and avoid other aircraft. The design of the resulting system, called ACAS sXu, will be completed in 2022 and will be a key capability enabling commercial sUAS operations. In support of this program, Lincoln Laboratory develops and validates algorithms and conducts flight tests by using its sUAS test bed. At right, Laboratory staff integrate sensors, communications, and autonomy components into one of several sUAS used in validation and flight test activities.



Engineering

Employing expertise in electrical, mechanical, structural, thermal, aerodynamics, optical, controls, and software engineering to build, integrate, and test systems for application in the development of advanced technology prototypes

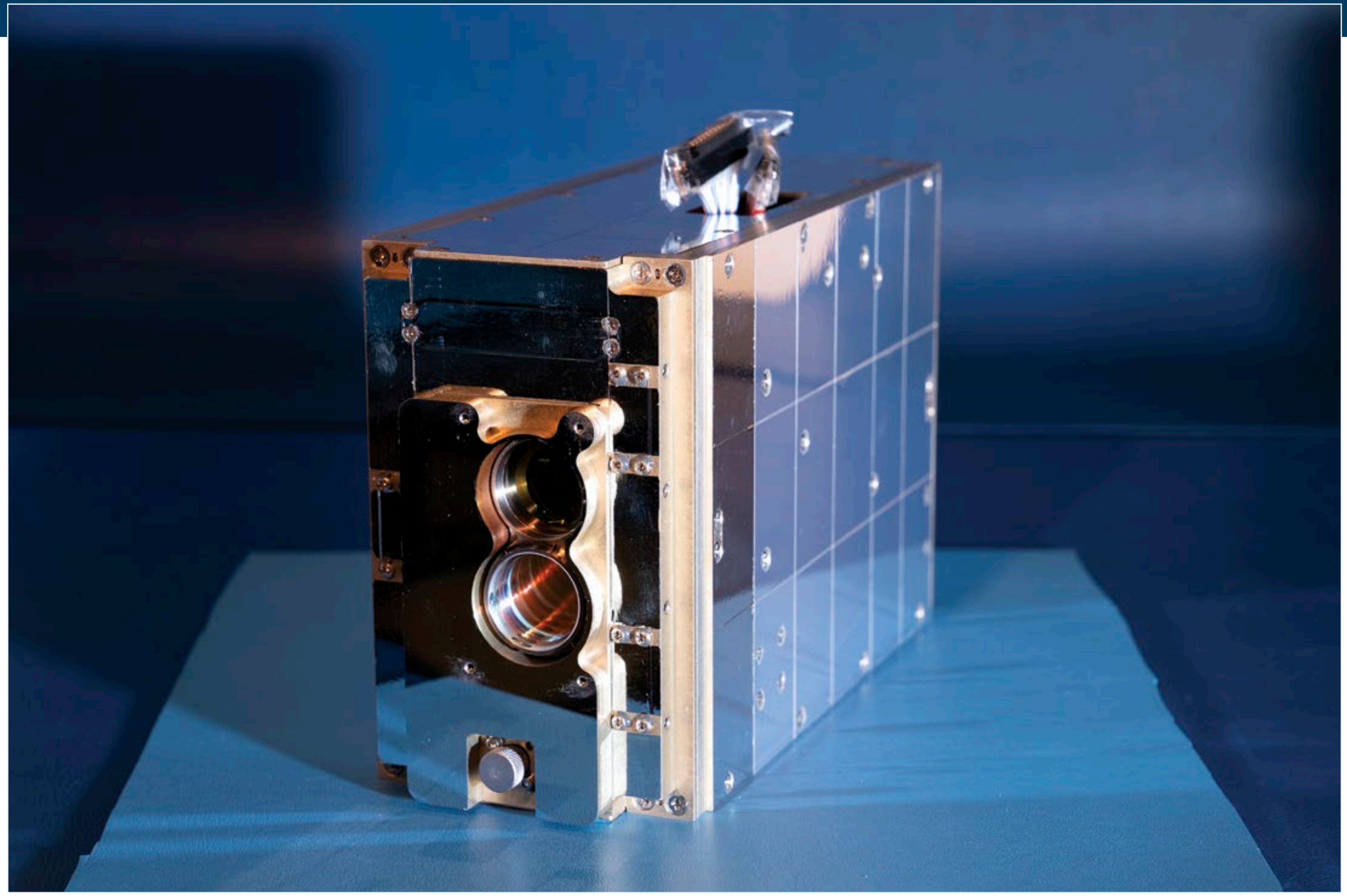
Leadership

Dr. Ted David
Division Head

Dr. Keith B. Doyle
Asst. Division Head

Vicky M. Gauthier
Asst. Division Head

Kristin N. Lorenze
Asst. Division Head



The Laboratory built a high-data-rate laser communication terminal for NASA to demonstrate 200-gigabits-per-second transmission from low-Earth orbit to a ground station. This 3U CubeSat terminal weighs 3 kilograms, has 2 terabytes of storage, and requires 100 watts of power to operate.

Principal 2021 Accomplishments

- The Digital Engineering Center was established to lead the Laboratory's development and adoption of model-centric approaches to prototype development, conduct novel research in digital engineering, and work with national agencies to drive digital engineering initiatives and studies.

- The Laboratory adopted a lean operations strategy to enhance mechanical and electrical parts fabrication.

- The development of future hypersonic interceptors and systems was enhanced by the development of unique modeling and design techniques. A state-of-the-art integrated simulation framework that optimizes the shape and materials of a vehicle on the basis of its aerodynamic and thermal behavior was prototyped over the past year. This algorithm capability is being actively transitioned and adopted by various external organizations.

- The Laboratory created flight software and firmware to accelerate the development of unmanned aerial vehicles (UAVs). State-of-the-art algorithms have been implemented to run on a single central processing unit without the use of a microcontroller to provide unified support for all common UAV types, including multirotors, fixed wings, and vertical take-off and landings.

- Using in situ closed-loop feedback error correction during diamond turning of optical substrates, the Laboratory developed techniques that allow increased resolution of optical systems with the use of freeform designs.

- The Laboratory increased its use of augmented and mixed reality technologies—including during assembly, integration, and testing—to enhance remote collaboration on projects and to accelerate the development of prototype hardware.

- The Laboratory is helping organizations identify capability gaps and solutions for warehouse modernization and automation by performing readiness assessments for technologies including inventory drones, automated storage, and autonomous materiel handling, such as self-driving forklifts and robotic arms enabled by machine learning.

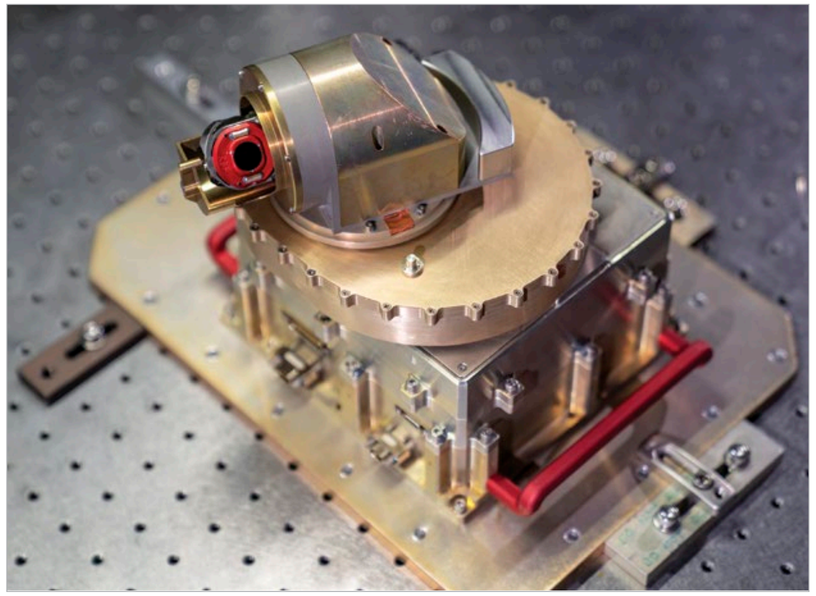
Future Outlook

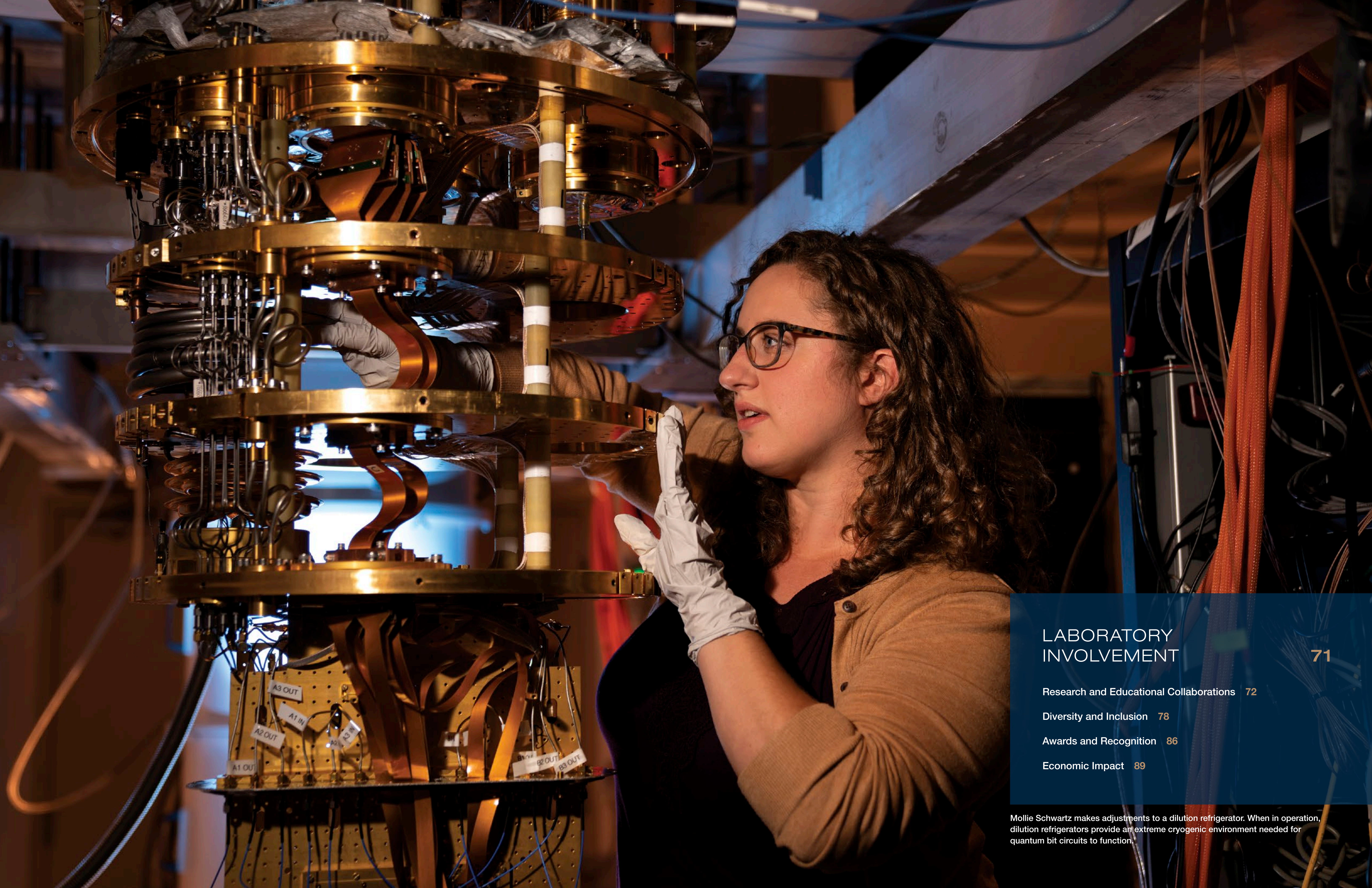
The Laboratory will increase its use of digital engineering to accelerate prototyping by integrating model-based practices into end-to-end prototyping workflow; leveraging shared data, models, and enhanced simulations; and using high-performance computing and artificial intelligence. The Laboratory will also extend connections to relevant Department of Defense strategic efforts to streamline the development of fully integrated platforms and deliver capabilities more rapidly with digital engineering practices.

The new Engineering Prototyping Facility is scheduled to open in 2027 and will provide a modern building that will more efficiently and effectively support the increasingly complex and challenging prototyping needs of the nation. The division is working with architecture firms that will provide the detailed design of the building and manage equipment moves. Construction is expected to start in 2025.

Mustang

Mustang is a bidirectional space-to-ground laser communication system built by Lincoln Laboratory that features a highly integrated mechanical and electrical design that provides a 10-megabits-per-second downlink capability from geosynchronous orbit and a 2-kilobits-per-second uplink capability from the ground. The payload mass is less than 5 kilograms, and it requires approximately 11 watts of unregulated bus power to operate. A microgimbal on the payload enables a large 2π steradian field of regard with a pointing stability of 20 microradians. A technology demonstration unit was delivered in July 2021.





LABORATORY INVOLVEMENT

Mollie Schwartz makes adjustments to a dilution refrigerator. When in operation, dilution refrigerators provide an extreme cryogenic environment needed for quantum bit circuits to function.

Research and Educational Collaborations

MIT MINI OCEAN GLIDER

Jean Sack, a technical staff member in Lincoln Laboratory's Energy Systems Group, and David Larson, an MIT graduate student, developed a low-cost mini ocean glider that can be used for underwater exploration and data collection. The gliders, which were initially conceived as part of a Beaver Works capstone course, are intended to be an open-source, inexpensive, and configurable system that can easily maneuver up and down in the water.

The glider's design is based on Blue Robotics' 4-inch watertight enclosure for remotely operated vehicles. The body of the glider consists of an acrylic tube, two wings on the outside for maneuvering, and a syringe that fills with water to sink and expels water to raise the glider to the surface. The inside of the glider—which includes a Raspberry Pi computer, GPS, inertial measurement unit, and lithium-ion battery pack mounted to a laser-cut acrylic structure—is customizable and reconfigurable to a variety of sensors. External ports include a temperature/pressure sensor, switch, and vent, with the option to add additional sensors as needed.

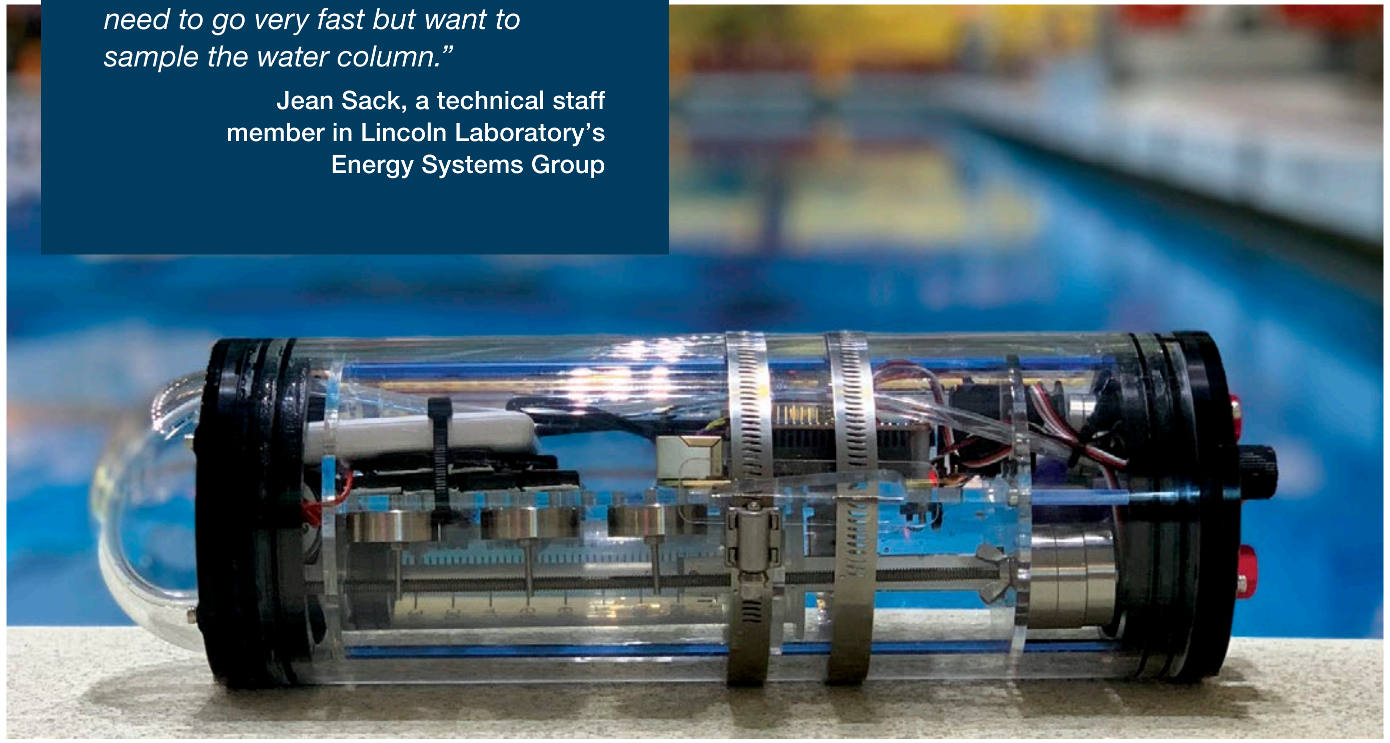
Because the basic glider costs less than $1,000 and can be built from commercial off-the-shelf parts, Sack believes it has many potential applications—for example, a swarm of gliders could be used to identify a point of interest underwater such as a wreckage or oil spill.

"The gliders have a lot of potential for low-cost, low-power underwater sensing applications where you don't need to go very fast but want to sample the water column," Sack said. "You could imagine sending out a bunch of these gliders, collecting a little bit of data, logging when you find something interesting, and then focusing your resources with more expensive sensors on that point of interest."

The glider has undergone testing at the MIT fitness center's pool and demonstrated a diving capacity of 5 meters, and with some modifications, it has the potential to dive to 30 meters.

"The gliders have a lot of potential for low-cost, low-power underwater sensing applications where you don't need to go very fast but want to sample the water column."

Jean Sack, a technical staff member in Lincoln Laboratory's Energy Systems Group

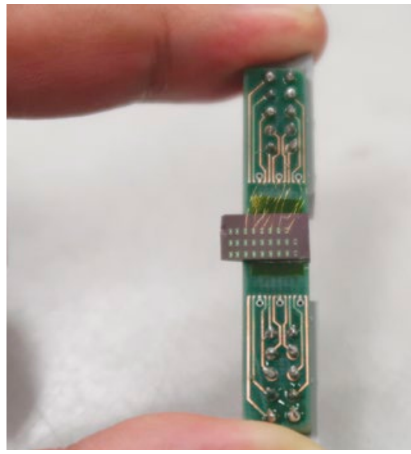


The miniature ocean glider is customizable and low cost, making it viable for a wide range of underwater operations.

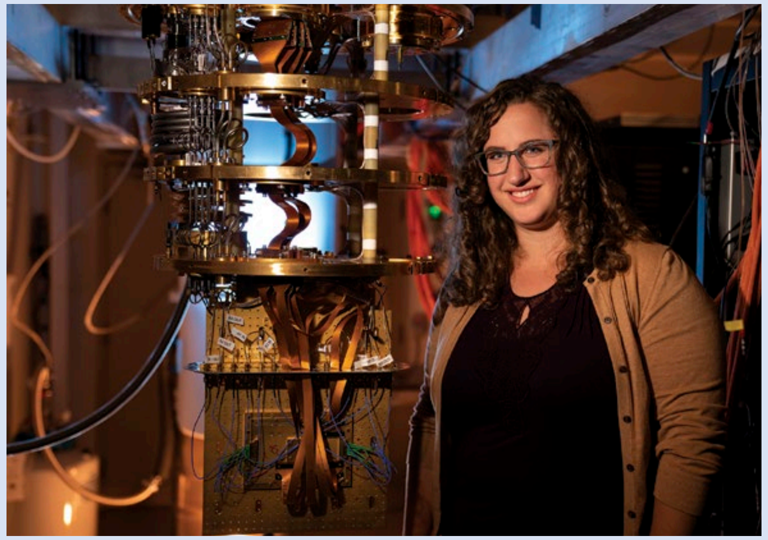
A TUNABLE METASURFACE FOR MINIATURIZED OPTICS

With the collaboration of Lincoln Laboratory researchers, engineers from MIT advanced their design of a tunable-metasurface optical device that can be electrically activated to change its material structure and, therefore, its optical properties. Key to this advancement was the discovery of a new phase-change material (a material that changes its atomic structure in response to heat) that is transparent to infrared light. Conventional phase-change materials are opaque, impeding their use in optical devices.

The new material is composed of germanium, selenium, antimony, and tellurium (GSST). To create the tunable metasurface device, the researchers produced an ultrathin, square film of GSST, patterned some 100,000 nanoscale structures into it, and integrated it onto a silicon chip. When the material is electrically heated, these nanostructures change their configuration. In optical applications, this reconfigurability could allow a laser beam to be precisely steered back and forth without the use of mechanical parts, or a single lens to be tuned to a desired focal length, replacing the need for an assembly of lenses. While this device is described by the inventors as a proof of principle, Laboratory researchers have demonstrated the scalability of this approach to large-area optics that could couple with existing systems, such as night-vision technology. The team is continuing to enhance the design of the device and hopes to eventually extend the transparency of the device to the visible spectrum.



Shown above is a closeup of the new tunable metasurface integrated onto a chip.
Photo: Yifei Zhang



Mollie Schwartz is an assistant leader of the Quantum Information and Integrated Nanosystems Group at the Laboratory and a thrust lead for the Quantum Systems Accelerator coalition.

A ROADMAP TO QUBIT CONTROL

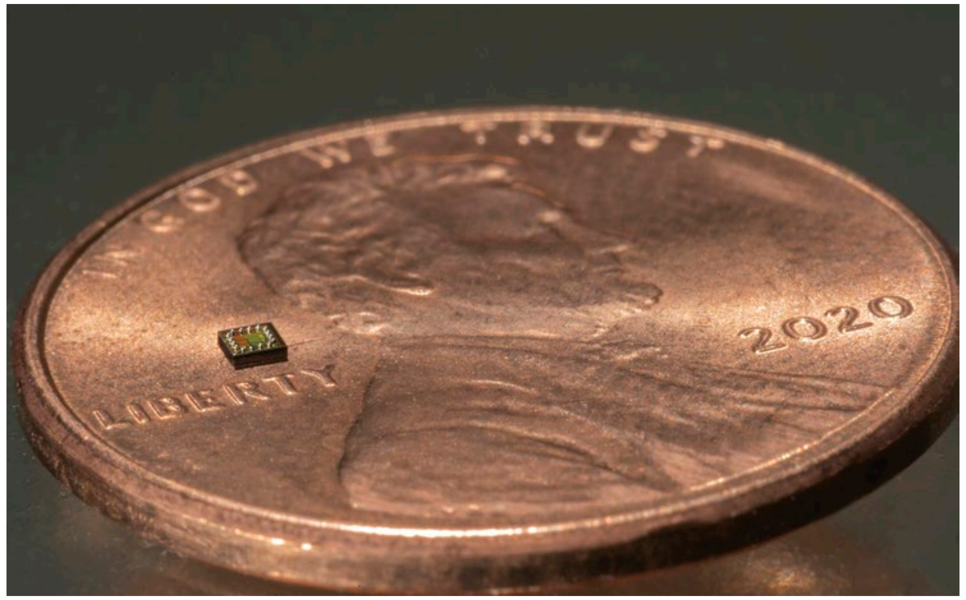
Lincoln Laboratory has been a leader for several decades in the development of quantum computing systems that may one day outperform modern computers. Last year, the Laboratory joined the Quantum Systems Accelerator (QSA), a research coalition spanning 15 institutes that aims to bridge the gap between current error-prone quantum processors and future, more capable machines. Today, the three leading approaches to developing quantum computers each use a different base—trapped ions, superconductors, or neutral atoms—to serve as the quantum bits (qubits) of the system. Though each approach is widely unique, they all present a similar, enormous challenge: building hardware that can precisely control and measure the qubits before their fleeting coherence time (which limits how long they can be used to perform useful calculations) expires.

To guide this research, Mollie Schwartz is helping the QSA develop a technology roadmap that sets a shared direction to developing qubit control systems, the specifications of which vary by platform. An expert in superconducting qubits, Schwartz serves as a QSA thrust lead in this area. In 2021, she joined fellow thrust leads in organizing roadmapping exercises, which offered an opportunity for researchers spanning the QSA to share lessons learned about each approach and map out solutions together.

"This roadmap is a mechanism for building a shared vision and highlighting areas where there can be closer collaboration across technology areas," Schwartz said. "We don't yet know which, if any, of these platforms is going to be the transistor of the quantum world, so we are pushing forward on all of them simultaneously."

>> Research and Educational Collaborations, cont.

FIBER SENSOR ARRAY BUOY

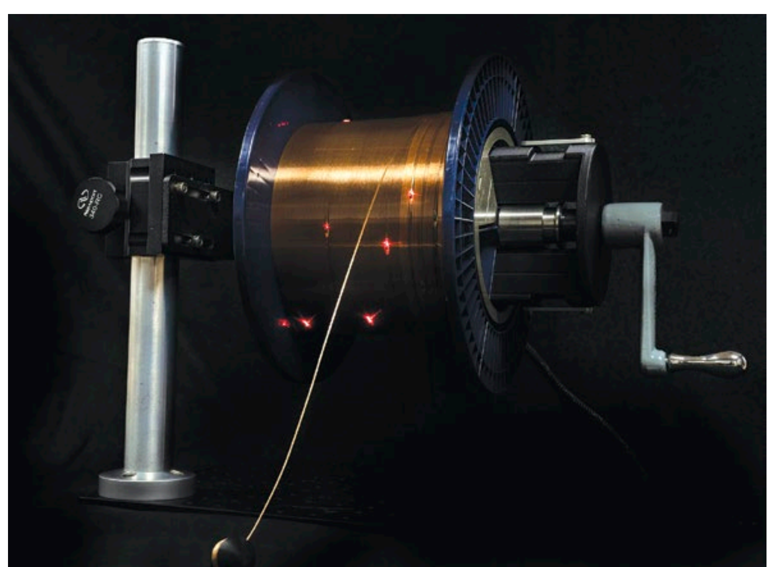


The integrated circuit shown above has been embedded into a fiber to enable a low-cost, persistent undersea monitoring system. The penny is shown for scale.

In partnership with the Advanced Functional Fabrics of America (AFFOA), Lincoln Laboratory is leveraging its experience in fabricating fibers with embedded electronics to develop long-length sensor arrays that can operate in the ocean. Researchers are exploring how such fibers may enable a lightweight, low-cost system that can persistently monitor the undersea environment. Measurements of water temperature, salinity, and pressure collected by this system would improve researchers' understanding of the ocean's changing dynamics. This capability is also important for naval operators, who need real-time undersea environmental data to accurately interpret acoustic signals.

To realize this capability, Laboratory and AFFOA researchers are developing a novel approach to embedding an array of sensors into polymer fibers that would extend hundreds of meters underwater. The approach uses a fiber-drawing technique, performed in the Defense Fabric Discovery Center, in which a block of polymer is heated and pulled into a long fiber. During this draw process, copper wires are fed into the middle of the fiber, providing electrical connection for an array of tiny sensors and integrated circuits that are embedded into the fiber by using a customized soldering and encapsulation process. The sensors are integrated throughout the length of the fiber to capture data at various depths. Electronics at the surface of the water would transmit the data to aircraft, ships, or satellites.

This technology has potential for addressing the needs of not only undersea monitoring but also ground and space-based applications.



Above, electronics are shown embedded in a fiber, where an encapsulant is used for protection from the water. At right, the resulting fiber has electronics and sensors integrated throughout its length. The illuminated red light–emitting diodes are distributed throughout the fiber, along with the sensors and electronics.

MILITARY FELLOWS PROGRAM

The Military Fellows Program is an annual program that offers military officers pursuing graduate degrees or advanced education the chance to engage in R&D at the Laboratory. Fellows are directly involved in developing capabilities important to national security, and, in turn, Laboratory staff benefit from the officers' unique insights. Since the program's start in 2010, more than 300 fellows have worked alongside Laboratory staff mentors.

Lincoln Laboratory military fellows gathered for a photo with U.S. Deputy Secretary of Defense Kathleen Hicks, center.

In July 2021, eight of the Laboratory's military fellows had the opportunity to meet U.S. Deputy Secretary of Defense Kathleen Hicks at the Beaver Works Center in Cambridge, Massachusetts, for a discussion about current technology development focus areas and modernization efforts at the Laboratory and the Department of Defense (DoD).

"Deputy Secretary Hicks was very interested in learning about the fellows' individual research areas in both their Lincoln Laboratory work and their studies on campus. I'm very glad that the Deputy Secretary was able to meet these talented officers and see how they are contributing to the Laboratory's mission and our nation's defense in the research and engineering domain," said Executive Officer to the Director and Chief of Staff Robert Loynd.

The Beaver Works Center was one stop on a tour of New England the Deputy Secretary embarked on to assess current technologies being used by the military and its modernization efforts. During their discussion, the fellows shared with Deputy Secretary Hicks the projects they worked on at the Laboratory spanning a variety of areas, including machine learning for cybersecurity and defense technologies. Deputy Secretary Hicks then briefed the group on the DoD's efforts to modernize its systems—especially through the use of artificial intelligence—and the challenges of modernization, including how to maximize the fuel efficiency of systems while minimizing their climate impacts.

"The most encouraging takeaway from our discussion with the Deputy Secretary of Defense is hearing that the DoD leadership's priorities are aligning with the current assignments of the Lincoln Laboratory military fellows, whether they be hybrid warfare, cybersecurity, or hypersonics," said U.S. Army Second Lieutenant Victor Kao, a military fellow. Kao works in the Systems and Architectures Group on research related to the Army's Strategic Long-Range Cannon.

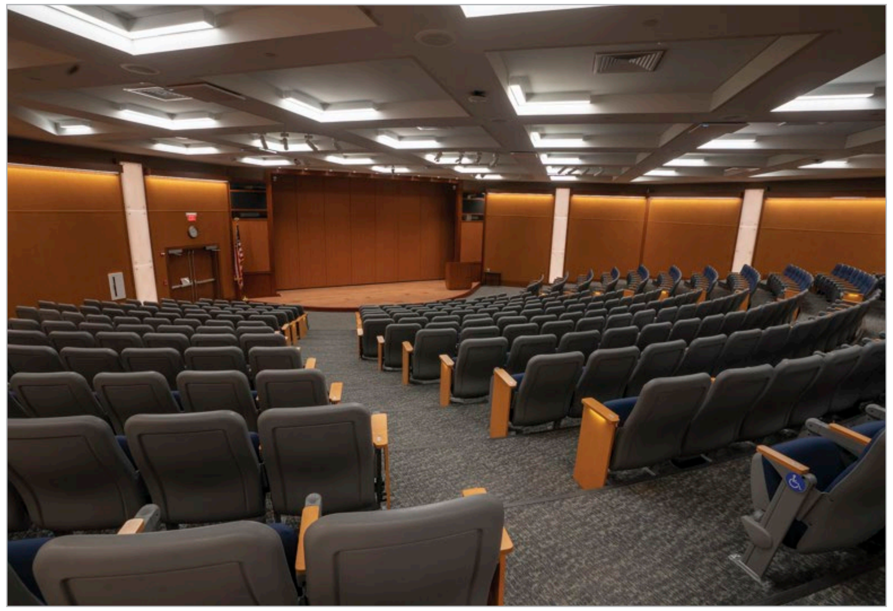
"It was exciting and invigorating to hear from Deputy Secretary Hicks about the priorities in today's DoD to modernize the joint forces for near-term and long-term competition with peer adversaries and to better utilize the talents of the men and women working in the [defense] department," said U.S. Air Force Second Lieutenant and military fellow Michael Geraghty, who works in the Laser Technology and Applications Group developing test setups for efficient testing of high-energy fiber-amplified lasers. He added, "It was clear that Dr. Hicks appreciated the Laboratory's efforts toward these priorities."

>> *Research and Educational Collaborations, cont.*

WORKSHOPS AND SEMINARS

The workshops and seminars hosted by Lincoln Laboratory cover a wide range of topics. At these events, Laboratory experts and nationally prominent guest speakers share their research into emerging technologies.

Because of the coronavirus pandemic, the following on-site workshops were canceled or postponed in 2021: Cyber Endeavor, A2/AD Systems and Technology Workshop, Counter-Human Trafficking Technology Workshop, Cyber Technology for National Security, Robustness of Artificial Intelligence System Assurance, Homeland Protection Workshop, Next Generation Identification and Awareness Technology Workshop, Human Language Technology and Applications Workshop, Space Control Conference, and the Defense Technology Seminar. Most of the workshops that were not canceled were held in a virtual format.



2021 Schedule of Lincoln Laboratory Workshops

APRIL

6–8 Advanced Technology for National Security Workshop

29 Artificial Intelligence (AI) for Cybersecurity Workshop

MAY

11–13 Air Vehicle Survivability Workshop

19–20 Lincoln Laboratory Communications Workshop

OCTOBER

5–7 Intelligence, Surveillance, and Reconnaissance Systems and Technology Workshop

12–14 Air, Missile, and Maritime Defense Technology Workshop

NOVEMBER

15 Human-Machine Collaboration for National Security Workshop

16–18 Recent Advances in AI for National Security

DECEMBER

3 Defense Technology Seminar for Military Fellows

14–15 Advanced Prototype Engineering Technology Symposium

2021 Off-site Workshops

The Laboratory also coordinates off-site workshops with partnering organizations. Laboratory involvement may be co-chairmanship of events, technical leadership of sessions, or co-sponsorship.

27–28 April
Air Traffic Control Workshop

17–18 May
Graph Exploitation Symposium

27–30 July
IEEE International Workshop on Wearable and Implantable Body Sensor Networks

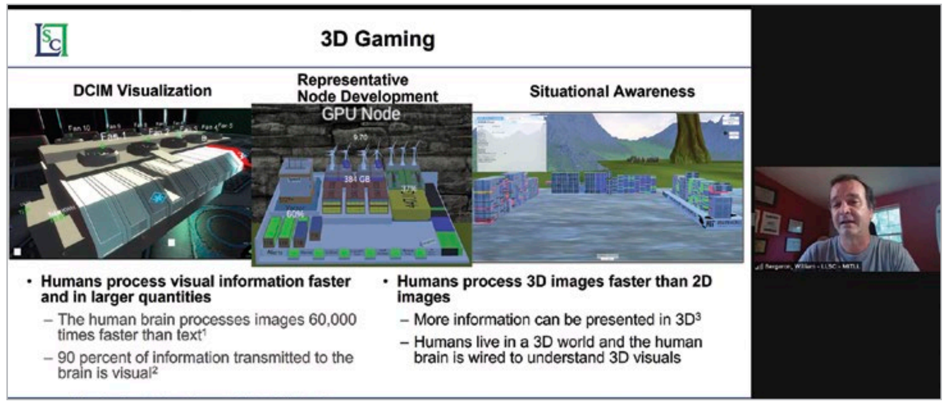
20–24 September
IEEE High Performance Extreme Computing Conference

8–9 November
IEEE International Symposium on Technologies for Homeland Security

13–14 December
IEEE International Workshop on Wearable Sensors and Devices, Artificial Intelligence and Wearables Markets

IEEE High Performance Extreme Computing Conference (HPEC)

Twenty-five years ago, Lincoln Laboratory established this conference, then called High Performance Embedded Computing, to provide the research and sponsor communities with a forum for discussing advances in high-performance computing. It has grown into the largest computing conference in New England and the premier conference in the world on the convergence of high-performance and embedded computing. Its community is interested in computing hardware, software, systems, and applications for which performance matters. Presentations at each conference have focused on high-performance extreme computing technologies such as AI/machine learning (ML), cloud computing, field-programmable gate array advances, cyber analysis, big data, graph analytics, and quantum computing. Lincoln Laboratory still serves as the technical organizer for the conference; Jeremy Kepner served as the chairman, Robert Bond as the senior advisory board chair, and Albert Reuther as the technical chair for the 2021 conference. The technical committee for this conference included Lincoln Laboratory staff Masahiro Arakawa, Peter Boettcher, Chansup Byun, Vijay Gadepally, Karen Gettings, Sanjeev Mohindra, Paul Monticciolo, Julie Mullen, Darrell Ricke, Siddarth Samsi, and Michael Vai.



William Bergeron presented "Real-Time Monitoring of Supercomputers with 3D Gaming Engine" during HPEC, arguing that humans can process information in 3D format much faster than in text or 2D format.

2021 Network and Distributed System Security Symposium

Hamed Okhravi chaired a session on trusted computing during the top-tier 2021 Network and Distributed System Security Symposium.

IEEE Engineering in Medicine and Biology Society's Public Forum on Healthcare Tech Industry Trends

Jeffrey Palmer spoke at a symposium on the digital health industry during the IEEE Engineering in Medicine and Biology Society's Public Forum on Healthcare Tech Industry Trends in August.

Graph Exploitation Symposium

The 2021 Graph Exploitation Symposium, hosted by MIT Lincoln Laboratory, brought together top network science researchers to share the latest advances and applications in the field. Network-based analysis continues to expand its reach and is applied to ever-more important areas of science, society, and defense with increasing impact. This virtual event focused on some of the year's most relevant issues, such as analyzing disinformation on social media, modeling the pandemic's spread, and using graph-based ML models to speed drug design. Several presentations at the symposium discussed the role of network science in analyzing influence operations, or organized attempts by state and/or non-state actors to spread disinformation narratives.

Diversity and Inclusion

A diverse workforce and an inclusive culture are more than just goals; they're vital to Lincoln Laboratory's technology mission. The Laboratory's culture must reflect the diversity of the nation it serves, and solving the nation's hardest problems takes the combined talents and unique views of many, sharing an environment where individuals are empowered to be their best. The Laboratory thrives when employees' views, experiences, and knowledge combine to drive innovation, and the ability to rapidly develop technology is made possible by a work environment in which employees are embraced for what they can do and for who they are. Diversity and inclusion are the Laboratory community members' responsibility to each other and to the nation they serve.

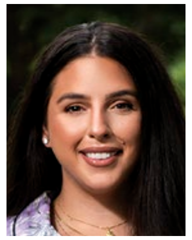
THE DIVERSITY AND INCLUSION OFFICE

In 2018, the Diversity and Inclusion (D&I) Office was established at Lincoln Laboratory. Its vision is to deliver a transformational competitive advantage to the Laboratory by becoming the national security industry exemplar in strategic D&I leadership and application. The D&I Office seeks to maximize individual and organizational performance and effectiveness by incorporating holistic D&I operations across people, business, and R&D systems and processes.

LEADERSHIP

Chevy Cleaves
Chief Diversity and Inclusion Officer

Alex Lupafya
Deputy Chief Diversity and Inclusion Officer



Samantha Jones
Assistant Program Manager

The D&I Office offers many resources and events for the Laboratory community, including seminars that cover a variety of topics such as racial bias in health; leadership development off-sites, where staff can learn how to lead effectively and inclusively; study groups; and Laboratory-wide educational and cultural initiatives.

Employee Resource Groups

Lincoln Laboratory's employee resource groups (ERGs) provide opportunities for connection between employees and support to staff members during the transitions they make as they advance in their careers. From helping new staff acclimate to the Laboratory's work environment, to encouraging professional development, to facilitating involvement in community outreach activities, the groups below help promote the retention and development of employees.

- **Lincoln Employees' African American Network (LEAN)**
  LEAN addresses issues faced by current and prospective African American employees, and participates in recruiting, community outreach, professional development seminars, and external networking.
- **Lincoln Employees with Disabilities (LED)**
  LED supports employees with disabilities and helps to create an efficient and accessible workspace that is inclusive to all. LED also supports employees who have family members with disabilities.
- **Lincoln Laboratory Hispanic/Latinx Network (LLHLN)**
  LLHLN fosters awareness of Hispanic culture and promotes networking and professional development for its members.
- **Lincoln Laboratory New Employee Network (LLNEN)**
  LLNEN is a social networking group for new hires to help them transition into the Laboratory culture.
- **Lincoln Laboratory Out and Proud Network (LLOPEN)**
  LLOPEN provides a forum for the LGBTQ+ community at the Laboratory and strives to make an environment in which LGBTQ+ employees can thrive and feel comfortable.
- **Lincoln Laboratory Veterans' Network (LLVETS)**
  LLVETS recognizes Laboratory employees who are U.S. veterans, supports veterans transitioning from the military, provides outreach to local active-duty troops and veterans, and informs members of activities and legislation affecting veterans.
- **Lincoln Laboratory Women's Network (LLWN)**
  LLWN promotes the recruitment, retention, and achievement of women employees and provides a forum for them to share experiences, strategies for success, and resources.
- **Pan-Asian Laboratory Staff (PALS)**
  PALS promotes and builds awareness of the variety of Asian cultures present at the Laboratory and offers opportunities for its members to congregate and share experiences.
- **Recent College Graduates (RCG)**
  RCG is a networking group for new employees transitioning from college life. Activities include social networking events and trips, community involvement, and peer-to-peer technical presentations.

>> Diversity and Inclusion, cont.

D&I: IT TAKES ENGAGED AND ACCOUNTABLE LEADERSHIP

Achieving a workplace commitment to diversity, inclusion, and equity takes the proactive support of management and the involvement of thought leaders from across the organization. Lincoln Laboratory is fortunate to have such a team of individuals dedicated to D&I goals:

- The Executive Diversity and Inclusion Council is cochaired by Lincoln Laboratory Director Eric Evans and Chief Diversity and Inclusion Officer Chevy Cleaves. The council represents a best practice designed to provide strategic oversight of, organizational support for, and accountability regarding D&I transformation while establishing and solidifying the Laboratory's position as an employer and partner of choice. The council is composed of 14 representatives across divisions, departments, offices, and levels.
- Fifteen members make up the Diversity & Inclusion Champions, one representing each division and department. This best practice supports coordination, strategic communications flow, alignment, and transformation through select senior leaders in each department and division.
- Each of the nine members of the Cross-Cultural Executive Sponsors for ERGs shares experience as a leader, strategist, and innovator with an ERG, helping advise and shape pathways that foster an inclusive, welcoming environment across the Laboratory.

Advancing Leadership in D&I

Over the last year, Lincoln Laboratory sponsored 32 individuals to participate in and benefit from the Diverse Leadership Development Collaborative program. Seeking to develop internal high-potential talent, the Laboratory teamed with two local organizations that help companies build a diverse pool of executive talent:

- The Partnership Inc. has evolved from its original focus on the advancement of African Americans in corporate Boston to an organization that supports multicultural professionals at all levels in an increasingly diverse and global workforce. The Partnership makes corporations and institutions more competitive in a global economy by helping them attract, develop, and retain talented multicultural professionals at all levels of leadership, and creating a corporate climate that encourages diversity and helps multicultural professionals thrive. The Partnership Inc. offers leadership development programs that help individuals at all stages of their careers define and reach their professional goals.
- Conexión's initial impetus was the growing corporate demand for Hispanic/Latinx talent. Conexión seeks to identify and fast-track the professionals who are ready to challenge the next level of increasing responsibilities. Through their leadership programs, Conexión helps prepare Hispanic/Latinx leaders to accept increasing responsibilities to ensure that not only Hispanic/Latinx communities and organizations but also the country thrive and prosper in the future.

A series of two-day D&I Leadership Off-sites encouraged Lincoln Laboratory managers to examine their personal and leadership styles, understand emotional and intercultural intelligence, evaluate their strengths and weaknesses, and explore ways to adapt their abilities to meet the requirements of an increasingly diverse workforce. The meetings discussed how leaders can foster successful team performance by better understanding how to leverage the impact of these skills in the context of current and future challenges and opportunities. These off-sites also prompted the creation of Communities of Practice with, and for, Laboratory leaders who serve as ERG Executive Sponsors and D&I Champions from each business unit. The feedback from participants in these off-sites has been overwhelmingly positive.

Conferences

An understanding of the ways individuals can both support and inclusively lead an increasingly diverse workforce is critical to an organization's ability to sustain a work environment that encourages teamwork, innovation, and success. Through a number of conferences, leaders and staff gained important insights into fostering D&I in the workplace and shared ideas on successful D&I initiatives.

At a prepandemic Massachusetts Conference for Women, Lincoln Laboratory staff networked with representatives from area organizations and potential new hires.

The 2021 Simmons Leadership Conference, sponsored for the 42nd consecutive year by the Simmons University Institute for Inclusive Leadership, was attended by 230 people from Lincoln Laboratory. This record Laboratory attendance was not only because the conference's virtual format allowed for a wide audience but also because the D&I Office and the Lincoln Laboratory Women's Network coordinated awareness of and admission to the event. In line with the theme of "authenticity and resiliency," the 2021 conference sought to empower women to become leaders who adapt to change and new challenges while retaining their principles and individuality. The conference features lively panel discussions, signature dialogues, and skill-building workshops on topics ranging from business strategy and innovation to career management.

Whitney Johnson, CEO of WLJ Advisors and author of *Disrupt Yourself: Putting the Power of Disruptive Innovation to Work*, led a discussion at the Simmons Leadership Conference on the value of challenging oneself as a way to build resilience. She referred to the quotation above from Simmons University President Lynn Perry Wooten to spark conversation.

The Massachusetts Conference for Women features workshops and seminars on relevant issues, such as business and entrepreneurship, health, and work/life balance. Since the first conference in 2005, this event has grown to attract more than 10,000 attendees annually. (In prepandemic years, all seats were sold out within minutes.) Staff from Lincoln Laboratory continue to enjoy this conference's opportunities for business networking, professional development, and personal growth.

The Women's Business Leadership Conference sponsored by Diversity Woman Media attracts women business leaders of all races, cultures, and backgrounds from the world's largest corporations and entrepreneurs from successful women-owned businesses. Recognized as the premier women's leadership conference for racial, ethnic, and gender diversity, the event gives attendees the chance to hear and learn from some of the most influential thought leaders and executives across the nation and world.

The EmERGe Leadership Summit is the only biannual conference designed specifically for members of ERGs and diversity councils. Attendees learn and share creative strategies for improving diversity, inclusion, and equity in the workplace. The 2021 event, again held virtually, explored how ERGs and diversity councils can better align themselves to their organizations' goals and business.

>> Diversity and Inclusion, cont.

GEM FELLOWSHIP PROGRAM

After taking a break last year because of the COVID-19 pandemic, the GEM program resumed in 2021 with 22 fellows joining the Laboratory for the summer. GEM is a network of leading corporations, laboratories, and research institutions that enables qualified students from underrepresented communities to pursue graduate education in science and engineering.

GEM fellows work as summer interns while completing their studies and receive financial support that is often the deciding factor in their pursuing graduate education. The internship process also allows companies to access and recruit talented candidates that they may not find otherwise. GEM fellowships at the Laboratory offer the students numerous returns, from networking opportunities to high-level research experience.

Miles Smith was one of 22 interns who joined the Laboratory through the 2021 GEM fellowship program.

GEM fellow Miles Smith worked in the Energy Systems Group to develop some state-of-health measurement techniques for a novel battery architecture that his supervisor is developing. About his fellowship experience, Smith said, "I have had a very positive experience and have found the support at Lincoln Lab to help me feel connected within the Lab community."

Lincoln Laboratory Featured in *Savoy* Magazine

The Laboratory was featured in an article about corporate diversity in the Spring 2021 Issue of *Savoy* magazine, a leading African American lifestyle and business magazine. The article highlighted how the Laboratory, alongside other national and global organizations, is transforming culture in the national security sector by drawing on the strengths and perspectives of a diverse and inclusive workforce. "At the Laboratory, a diverse workforce and an inclusive culture are more than just goals; they're vital to our mission," Chevy Cleaves, Lincoln Laboratory Chief Diversity and Inclusion Officer, said in the article. "Innovation thrives at the nexus of inclusion and diversity, and we are committed to leveraging talent from all across the nation to help us identify and solve some of the world's most challenging problems."

Shown at left is a graphic printed alongside Lincoln Laboratory's featured article in the Spring 2021 Issue of *Savoy* magazine.

LABORATORY D&I EVENTS AND INITIATIVES

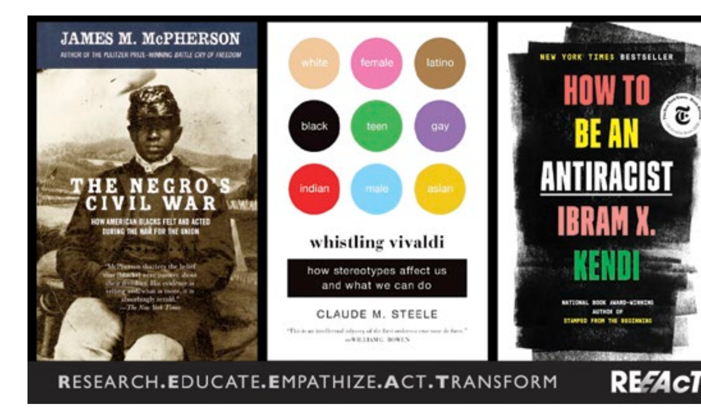
RE^{2}AcT Study Groups

Members of the RE^{2}AcT study group reading the book *Just Mercy* gathered for a virtual group photo.

RE^{2}AcT (Research. Educate. Empathize. Act. Transform) is an ongoing initiative at the Laboratory that was developed by the D&I Office in summer 2020 to help members and leaders of the Laboratory community develop the foundation necessary to strategically respond to the challenge of systemic racism while building a more diverse and inclusive organization.

In fall 2020, the D&I Office launched the RE^{2}AcT study groups, which allow Laboratory employees to read and discuss various books about social issues in America. The goal of the study groups is to create an inclusive and safe atmosphere for small group learning and discussion while identifying additional areas for research, learning, and development.

In 2021, study group members read and discussed the following books: *Just Mercy* by Bryan Stevenson; *Supreme Inequality* by Adam Cohen; *In the Shadow of Statues* by Mitch Landrieu; *The Soul of America* by Jon Meacham; *Biased* by Jennifer Eberhardt; *Stamped from the Beginning* by Ibram Kendi; *The Negro's Civil War* by James McPherson; *Whistling Vivaldi* by Claude Steele; and *How to be an Antiracist* by Ibram Kendi.



>> Diversity and Inclusion, cont.

Dr. Martin Luther King Jr. Celebration

On February 4, the Lincoln Employees' African American Network (LEAN) sponsored their eighth Annual MLK Celebration, which was inspired by Dr. Martin Luther King Jr.'s "I Have a Dream" speech. The theme of the event was "Fulfilling the Dream with Courage and Hope." The event opened with a video montage that asked several Laboratory employees about what Black History Month means to them. Karl Reid, Executive Director of the National Society of Black Engineers, delivered the event's keynote address. Reid began his keynote, titled "Towards Inclusive Excellence: Fulfilling the Dream with Courage and Hope," by asking what Dr. King's dream would look like if it were to be brought forward into contemporary times. Reid's answer, laid out throughout his keynote, was that "diversity and equity are a means to an end, and the end is inclusive excellence—it's creating an inclusive environment where everyone can play a role and feel a part of an organization."

Karl Reid, Executive Director of the National Society of Black Engineers, presented the keynote address at the Laboratory's 2021 MLK Celebration.

Cultivating Leadership, Achievement, and Success Symposium

Members of the Our Voices, Our Vote (OVOV) team accepted their Strength in Unity awards. The OVOV team organized events in 2021 to recognize the centennial anniversary of the 19th Amendment, which guaranteed American women the right to vote.

The Laboratory held its fourth annual Cultivating Leadership, Achievement, and Success (CLAS) Symposium in March 2021. The Lincoln Laboratory Women's Network launched the symposium in 2018 with the goal of furthering cultural development in the workplace, providing training opportunities for leadership skills, and highlighting people who make the Laboratory a better place to work. General David Thompson, the first Vice Chief of Space Operations for the United States Space Force, gave the keynote address in which he spoke about the importance of selecting the right leadership, effectively leveraging talent, and leading an organization through big changes. The symposium also included two panel discussions about leadership for the Laboratory of the future and a course about best practices for building strong virtual teams. The event concluded with an awards ceremony recognizing employees for their positive impacts on Laboratory culture, excellence in mentorship, and contributions to Laboratory events and initiatives.

Asian Pacific American Heritage Month

MIT Professor Emma Teng gave an overview of Asian American history as part of the Laboratory's Asian Pacific American Heritage Month celebration.

Throughout the month of May, communities at the Laboratory and across the country observed Asian Pacific American Heritage Month—a period of paying tribute to the generations of Asian and Pacific Islanders who have enriched America's history and are instrumental in its future success. The Pan-Asian Laboratory Staff (PALS) hosted a series of events in May that included a discussion with Adrienne Su, a poet and the author of *Peach State*; a trivia event about Asian American and Pacific Islander history, activism, and entertainment; and a historical overview of Asian Americans given by MIT Professor of Asian Civilizations Emma Teng.

Celebrating Juneteenth

On June 17, the same day President Joseph Biden signed a bill to designate Juneteenth as a new national holiday, members of LEAN and the Laboratory community came together for a virtual event that consisted of a moderated panel discussion and open discussion about the significance of Juneteenth. Prior to the event, participants were asked to view two videos that give context to the history and meaning of Juneteenth. Nearly 400 people attended the discussions to share their reflections, questions, and comments regarding the videos and Juneteenth. On June 18, the Laboratory observed Juneteenth as a federal holiday for the first time.

LEAN Chair Kofi Williams led a virtual discussion about Juneteenth's historical and societal significance.

Consuelo Cuevas, co-chair of the Hispanic/Latinx Network, spoke in a video that asked Laboratory employees what Hispanic Heritage Month means to them.

Hispanic Heritage Month

From September to October 2021, the Laboratory's Hispanic/Latinx Network hosted virtual events to celebrate national Hispanic Heritage Month. The month's events included a technical presentation about a data-driven method being used to monitor the COVID-19 pandemic in Puerto Rico, a technical and inclusivity talk from an integration and test manager at NASA, a presentation from an infectious disease specialist on the effects of the pandemic on minority and underrepresented groups, and other virtual events that celebrate Hispanic culture.

Awards and Recognition

2020 MIT Lincoln Laboratory Technical Excellence Awards

David R. Crompton, for excellence in building complex hardware systems that are critical to the development of space systems, optical payloads, and precision mechanisms, and for expertise in structural analysis and testing that enable innovative engineering solutions for ground, sea, air, and space prototype systems.

Dr. Alan J. Fenn, for innovation in developing antennas and adaptive arrays that provide revolutionary capabilities for ground-, air-, and space-based radar, electronic warfare, communications, and sensing systems, and for leadership in building a world-class facility for simulating, prototyping, and testing novel antenna and electromagnetic systems at Lincoln Laboratory.

2020 MIT Lincoln Laboratory Early Career Technical Achievement Awards

Dr. Nicholas D. Hardy, for system analysis expertise and technical insights that have enabled his major contributions to critical challenges in modern optical communications technology, including the demonstration of entanglement-based quantum communications over fiber and free-space channels and of high-rate undersea laser communications.

Dr. Meghan E. Ramsey, for demonstrating excellent technical capabilities and leadership in multi-agency programs that are addressing the threats from emerging pathogens, the pathology of infectious diseases, the development of medical countermeasures, research in aerosol science, and biodefense response and recovery.

2020 MIT Lincoln Laboratory Best Paper Award

Dr. William Loh, **Jules M. Stuart**, **Dr. David L. Reens**, **Colin D. Bruzewicz**, **Dr. Danielle A. Braje**, **Dr. John Chiaverini**, **Dr. Paul W. Juodawlkis**, **Dr. Jeremy M. Sage**, and **Dr. Robert P. McConnell**, for "Operation of an Optical Atomic Clock with a Brillouin Laser Subsystem," published in *Nature*, Volume 588, December 2020.

2020 MIT Lincoln Laboratory Best Invention Award

Dr. Melissa A. Smith, **Donna-Ruth Yost**, **Noah Siegel**, **Dr. Daniel Freeman**, and **Dr. Paulo Lozano**, for the invention of Electrospray Device and Fabrication Methods.

2021 Election to the National Academy of Engineering

Dr. Marija Ilic was named a member of the National Academy of Engineering (NAE) for her contributions to electric power system analysis and control. The NAE is a private, nonprofit institution that brings eminent engineers together to provide independent advice to the federal government on engineering and technology.

2021 IEEE Fellow

Dr. Robert T-I. Shin, for leadership in electromagnetic modeling of radar systems and in microwave remote sensing. The IEEE is the world's largest technical professional organization and annually confers the rank of Fellow on senior members whose body of work has advanced innovation in their respective fields.

2021 FLC Northeast Regional Award for Excellence in Technology Transfer

The Federal Laboratory Consortium for Technology Transfer (FLC) selected **Lincoln Laboratory** as the Northeast region's winner of its award for outstanding achievement in technology transfer. The award recognizes two Laboratory technologies: Forensic Video Exploitation and Analysis, a suite of analytic tools to help investigators review surveillance video footage; and Keylime, a software architecture that increases the security and privacy of data and services in the cloud.

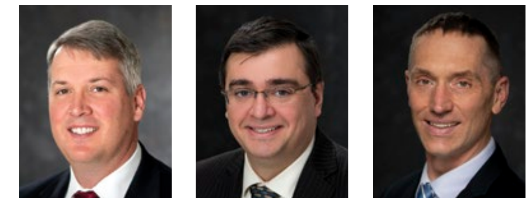
2021 Fellow of the Society for Industrial and Applied Mathematics

Dr. Jeremy Kepner, for contributions to interactive parallel computing, matrix-based graph algorithms, green supercomputing, and big data. The Society for Industrial and Applied Mathematics helps build cooperation between mathematics and the fields of science and technology to solve real-world problems.

2020 IEEE Boston Section Distinguished Service Award

Dr. Albert I. Reuther, for his dedicated support of the IEEE Boston Section's 2020 High Performance Extreme Computing Conference (HPEC) and his efforts to virtualize the conference in response to the COVID-19 pandemic. Reuther serves as the technical chair of the IEEE HPEC conference.

AIAA Associate Fellows



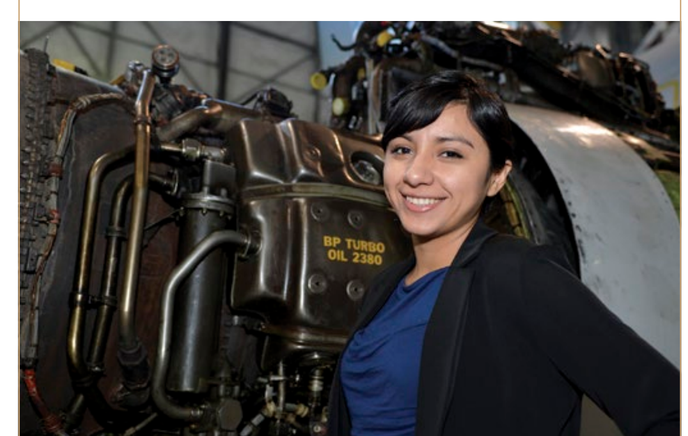
Above left to right, **Dr. William J. Blackwell**, **James R. McIntire**, and **Dr. Mark J. Silver** were selected to the 2021 class of Associate Fellows of the American Institute of Aeronautics and Astronautics (AIAA).

2021 MassTLC Mosaic Award

Awarded to **Chevalier "Chevy" Cleaves** by the Mass Technology Leadership Council (MassTLC) for his work in creating access and opportunity for future leaders. Cleaves received the award for his work at the Laboratory as well as his past work as the first Chief Diversity Officer at the U.S. Air Force and first Vice President of Global Diversity and Inclusion at Boston Scientific.

Inclusion in the Massachusetts HERstory

Yari Golden-Castano was one of 91 women, from pioneer days to today, with ties to Massachusetts who have been selected by Massachusetts Senate President Karen Spilka to be featured in the second edition of the HERstory project display and video. The project acknowledges these women's roles as trailblazers in their given fields and selected these women of color who have inspired young people to work for a better world.



2021 MIT Lincoln Laboratory Administrative and Support Excellence Awards

Administrative category: **Joseph W. Orender**, above left, for outstanding supervision of the teams that maintain the Engineering Division's integration and environmental test laboratories; **Kristi H. Wakeham**, above right, for her role in tracking and responding to employees' COVID-19 reporting and concerns, and for assisting employees with procedures for medical leaves.

Support category: **Kathleen L. Cable**, above left, for her excellent efforts as the Division Administrative Assistant of the Homeland Protection and Air Traffic Control Division, and her support to special events and committees at the Laboratory; **Steve S. Salsberry**, above right, for his sustained, exceptional leadership of the operations of Lincoln Laboratory's chilled water plant.

>> Awards and Recognition, cont.

2021 ICAO Walter Baginhi Award

The International Civil Aviation Organization (ICAO) presented this award to **Dr. Vincent A. Orlando** for his sustained and significant contributions to international aviation.

2021 Gold HIRE Vets Medallion Award

Awarded to **Lincoln Laboratory** for the second consecutive year in recognition of efforts to recruit, hire, develop, and retain veteran employees. The Laboratory was one of 849 employers awarded a medallion across the nation.

2021 Award for Excellence in Diversity and Inclusion

At the North American HR Executive Summit, a gathering hosted by Executive Platforms for human resources (HR) executives, **Lincoln Laboratory** was honored with this award, which is given to industry-leading organizations that have made exceptional efforts to build equality and openness into the fabric of their workforce culture.

2021 James A. Cogswell Award

Awarded to the **Huntsville Field Site** by the Defense Counterintelligence and Security Agency for outstanding industrial security. This award is given to facilities that have established and maintained a security program that exceeds basic National Industrial Security Program requirements.

2020 Superior Security Rating

Awarded to **Lincoln Laboratory** by the U.S. Air Force for the 15th consecutive year. The rating represents the Laboratory's commitment to safeguarding sensitive and classified information.

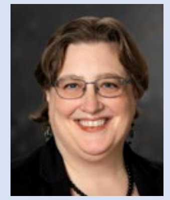
2020 Department of the Air Force–MIT Artificial Intelligence Accelerator (AIA) Awards

Awarded to two teams involving Lincoln Laboratory staff. One team received the Director's Award, which highlights "excellence and impact with a focus on collaboration across the AIA and with stakeholders," for their efforts on the Earth Intelligence Engine to build weather and climate resiliency. **Dr. Mark Veillette** led this team, which included **Dr. Allison Chang** and **Esther Wolf**. The other team received the Challenge Award for designing and implementing two challenges—competitions that engage academia, industry, and the public in solving a common problem—focused on optimizing Puckboard, a web-based software application for scheduling aircrews to mission and training flights. This team was led by **Michael Snyder**, and the other members included **Dr. Amy Alexander**, **Kendrick Cancio**, **Dr. Jeremy Kepner**, and **Jessamyn Liu**.

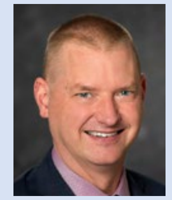
2021 MIT Excellence Awards

Bringing out the Best category:

Dr. Martine M. Kalke

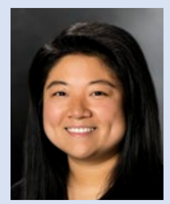


Dr. Jonathan D. Pitts



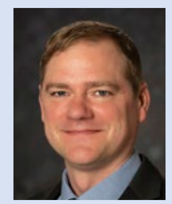
Embracing Diversity, Equity, and Inclusion category:

Alice Lee



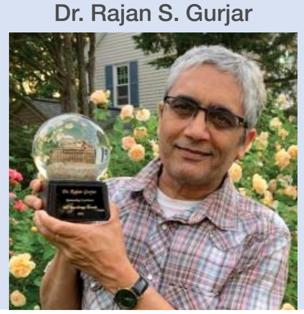
Serving Our Community category:

Zachary Sweet

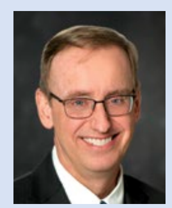


Outstanding Contributor category:

Dr. Rajan S. Gurjar



David F. Johnson



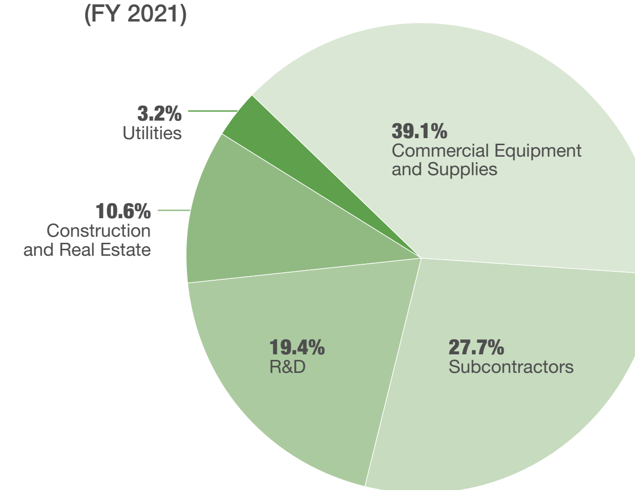
2021 Cultivating Leadership, Achievement, and Success Awards

Employee Resource Group Excellence Award: **Alice Lee**
Equity Award: **Dr. Bonita J. Burke**
Outstanding Mentor Award: **Dr. Bryan Ward**
Leadership Award for Advancing Organizational Culture: **Dr. Martine M. Kalke** and **Heather E. Rogers**
Peer Award for Cultural Impact: **Ngaire K. Underhill**
Emeritus Award: **Gerald C. Augeri**
Strength in Unity Award: **Our Voices, Our Vote Committee—Julie A. Arloro-Mehta, Christine M. Carlino, Stephanie B. Darga, Marie L. Dow, Jeannine M. Fallon, Matthew R. Ford, Barbra Gottschalk, David R. Granchelli, Suellen E. Green, Susan W. Hersey, Samantha Jones, Tammy M. Ko, Erin I. Lee, Rowena J. Lindsay, Dorothy S. Ryan, Lidia M. Scovil, Dr. Stephanie H. Sposato,** and **Nora B. Zaldivar**

Economic Impact

Lincoln Laboratory serves as an economic engine for the region and the nation through its procurement of equipment and technical services. During fiscal year 2021, the Laboratory issued subcontracts with a value of $472.7 million to businesses in all 50 states, Washington, D.C., and Puerto Rico. The Laboratory purchased $232.4 million in goods and services from New England companies, with $178.2 million in contracts awarded to Massachusetts businesses. The Laboratory contracts with universities outside of MIT for basic and applied research. These research subcontracts include expert consulting, analysis, and technical support.

Contracted services*
(FY 2021)



**Estimates from $472.7M, total FY21 spend*
– Includes orders to MIT – $5.5M
– Figures are net awards less reductions

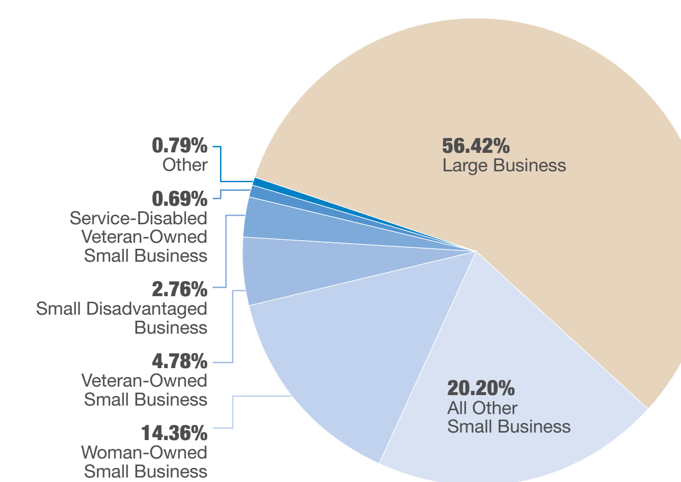
STATE	$ MILLION
Massachusetts	178.2
California	59.2
New Hampshire	40.8
Virginia	20.7
Texas	19.9
Illinois	12.6
New Jersey	10.7
All Other	130.6
Total*	472.7

**Includes orders to MIT – $5.5M*

Small Business Office

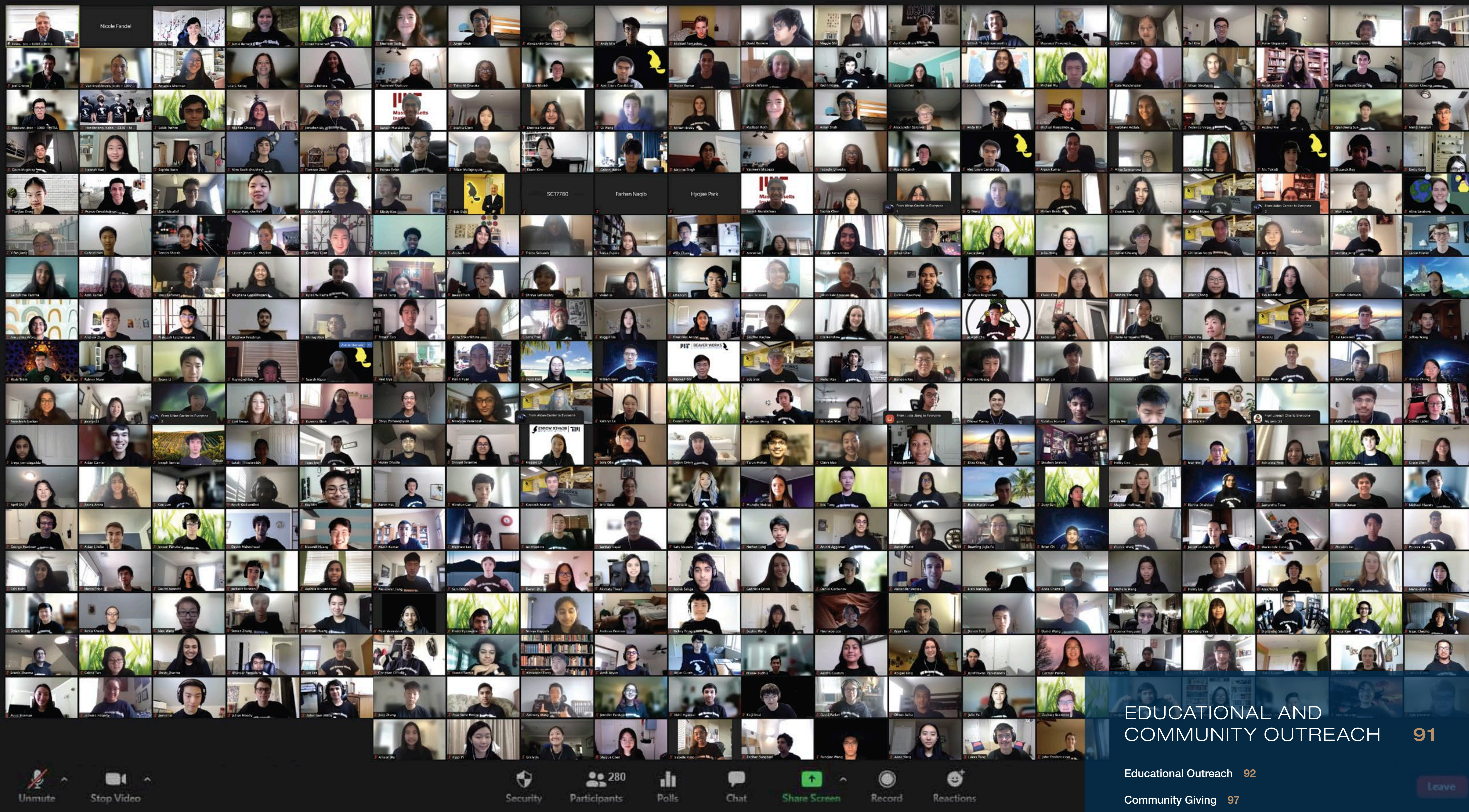
Small businesses—which supply construction, maintenance, fabrication, and professional technical services in addition to commercial equipment and material—are significant beneficiaries of the Laboratory's outside procurement program. In 2021, more than 43% of subcontracts were awarded to small businesses of all types (as reported to the Defense Contract Management Agency). The Laboratory's Small Business Office is committed to an aggressive program designed to afford small business concerns the maximum opportunity to compete for purchase orders.

Contract awards by category of businesses (FY 2021)*



**As reported to the Defense Contract Management Agency (DCMA)*

43.58%
Total for all small business



EDUCATIONAL AND COMMUNITY OUTREACH 91

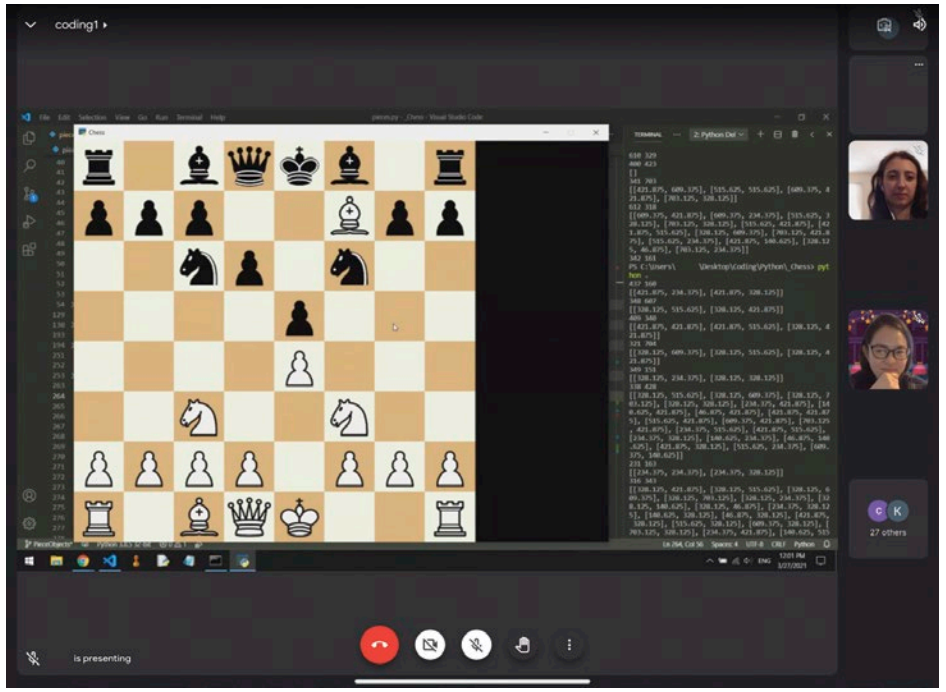
This year's Beaver Works Summer Institute was held in a virtual format, enabling the program to include more students and more courses. The course offerings were increased from 9 to 13 classes, and a record 351 students were accepted, compared to last year's 178 students.

Educational Outreach

LINCOLN CODERS

The first Lincoln Coders educational outreach program for sixth and seventh grade students from middle schools in nearby Lincoln, Massachusetts, and Hanscom Air Force Base took place in the spring. Thirteen program facilitators from the Laboratory's Recent College Graduates employee resource group worked with 17 students for seven weeks to teach them how to code. Each student chose to work in Scratch, JavaScript, or Python. With the help of the facilitators, students built their own unique chatbots, fighting games, and chess game in Python; meteor-catching games in JavaScript; and animations and interactive games in Scratch.

Olivia Brown and Victoria Helus gave a brief presentation on artificial intelligence and machine learning, after which the students worked on their coding projects and then presented the progress they had made at the end of the class. The goal of the program was to teach the students to be brave, resilient, creative, and purposeful through coding.

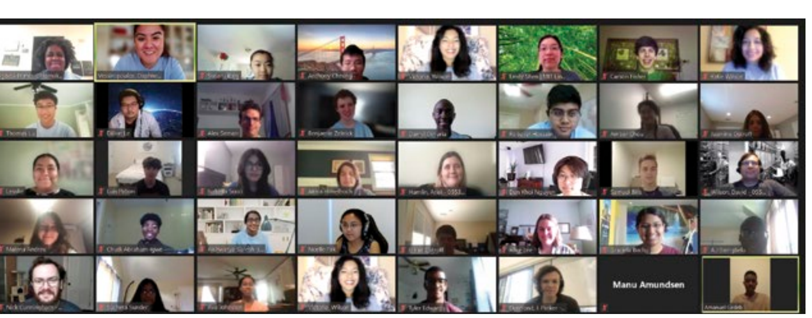


After seven weeks of hard work, Hanscom and Lincoln Middle School students in Lincoln Coders presented final projects, like this chess game code. Mentoring of students by Laboratory staff was key to the success of this new program.

"I didn't learn how to code until college. Having this experience at that age would have been awesome," said Adam Gjersvik, a Lincoln Coders facilitator. "I loved being able to give students that opportunity, especially given the growing importance of knowing how to code in society today."

LINCOLN LABORATORY CIPHER

For seven years, Lincoln Laboratory has offered students interested in mathematics and cryptography a weeklong summer workshop called Lincoln Laboratory Cipher (LLCipher). In August 2021, the program was held virtually for 30 high school students from across the country eager to learn advanced mathematics. Laboratory staff volunteered as primary instructors and assisted students in understanding modern theoretical cryptography.



Thirty high school students from across the country participated in LLCipher this year and learned course material from Laboratory technical staff.

After learning the basics of cryptography, students learned how to build a secure encryption scheme and digital signature. Typically, the workshop curriculum includes hands-on demonstrations and activities that reinforce basic lessons of classical and modern cryptography; however, this year, these activities were introduced online. Aspects of abstract algebra, number theory, and complexity theory were included in the curriculum, as well as topics of active research interest in cryptography, such as zero-knowledge proofs and multiparty computation.

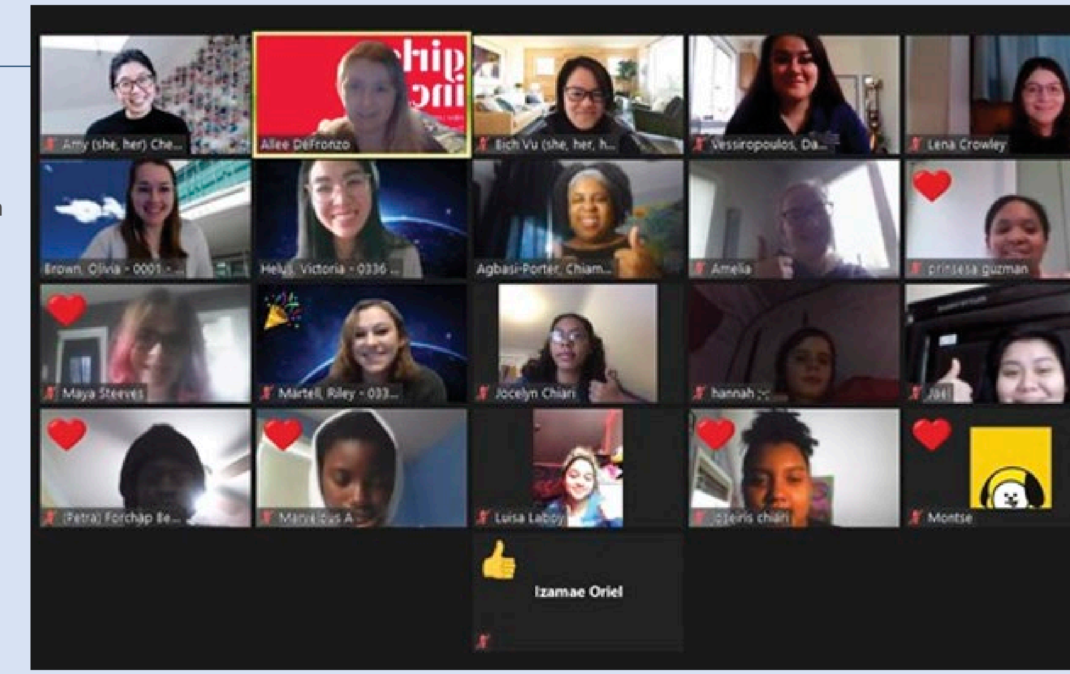
G.I.R.L. ARTIFICIAL INTELLIGENCE/MACHINE LEARNING (AI/ML) WORKSHOPS

G.I.R.L. AI/ML Workshop: Lynn

On December 30, 2020, Laboratory staff members hosted a Girls' Innovation Research Lab (G.I.R.L) workshop in which they partnered with Girls Inc. of Lynn, Massachusetts, to teach middle and high school girls the basics of artificial intelligence (AI) and machine learning (ML).

For this virtual workshop on AI, Victoria Helus and Olivia Brown led the planning for the 20 attendees. Riley Martell, Amy Chen, and Bich Vu explained how AI and ML differ from standard computer programming, how to tell if a technology is using AI, and how AI algorithms are designed. "One unique aspect of our workshop is that it did not involve any computer programming," said Brown. "Because the workshop was code free, the girls could focus on learning the high-level concepts behind AI, rather than spending their time trying to get code to run."

The girls used candy to explore an algorithm design technique called a decision tree. The girls were tasked with sorting the candy by asking progressively more specific questions—such as, is the wrapper brown, does the candy contain chocolate, and does the candy contain nuts? The girls were encouraged to be creative and decide for themselves what features were important in organizing their "data." Staff hope that these events will give girls confidence by disrupting the notion that only certain people belong in science and engineering.



At the virtual G.I.R.L. AI/ML Workshop for Girls, Inc. of Lynn, 20 middle and high school girls were introduced to the concepts of artificial intelligence, machine learning, and programming.

G.I.R.L. AI/ML Workshop: Lowell

As proof of the success and popularity of the AI/ML Workshop in December, the same workshop was requested by Girls Inc. of Lowell, Massachusetts, in April. Victoria Helus and Olivia Brown led the workshop, while Riley Martell and Yari Golden-Castano assisted with presentations. These volunteers shared their personal stories with the almost 20 girls, detailing what inspired them to follow a technical career path, what their current jobs entail, and why they love working in the AI/ML field.

G.I.R.L. AI/ML Workshop: Hanscom

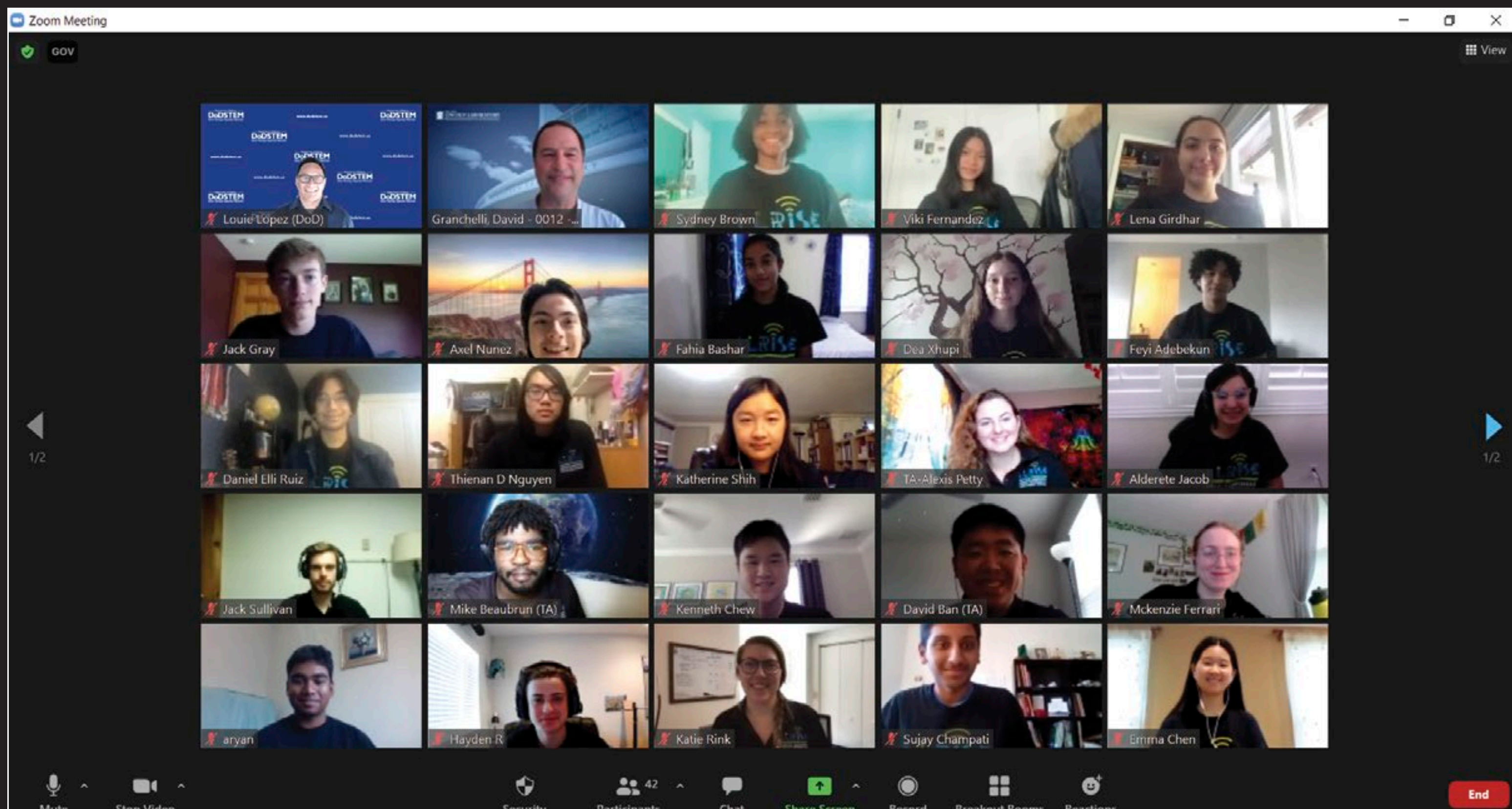
A third workshop on AI/ML was held in June for seventh grade students in Hanscom Middle School. The 63 students learned what constitutes AI and practiced building decision trees. A timely addition was a discussion about biases in ML and why it's important to be conscious of bias.

The lead presenters were Victoria Helus and Olivia Brown. The event was organized by Yari Golden-Castano, who was assisted by volunteers Amy Chen, Cassian Corey, Peijun Shao, Adam Kern, Nathan Vaska, and Andrew Schoer.

Hanscom Middle School educators were grateful for the presentation and indicated that several of the students said it was the best thing they've done all year.

>> Educational Outreach, cont.

LINCOLN LABORATORY RADAR INTRODUCTION FOR STUDENT ENGINEERS (LLRISE)



LLRISE participants listened as Louie Lopez, Director of DoD STEM (top left), provided an overview of DoD STEM opportunities and scholarships that can further the academic careers of students or help prepare them for careers in the DoD.

The tenth Lincoln Laboratory Radar Introduction for Student Engineers (LLRISE), a two-week program for 31 rising high school seniors, was held in July 2021. The program was offered in a virtual format, just as in 2020, and explained the basics of radar systems and three different radar modes: Doppler radar, pulsed coherent radar, and synthetic aperture radar. Laboratory staff volunteering their time to prepare and host the lectures included Ryan Bohler, David Brigada, Mark Jones, Aryk Ledet, David Maurer, David Scott, George Pantazis, and Andrew Volpe.

The students in the program came from a wide variety of backgrounds that are typically not well represented in STEM fields. The 2021 class included students who will be first-generation college students, are from low-income backgrounds, and whose race is underrepresented in STEM.

Prior to the course, the students were shipped a radar kit that they could use for building their own experiments with the help of mentors and teaching assistants via Zoom. The participants were provided with radar code but also learned basic coding in Python so that they could develop their own experiments and simulations using their kits. Many of the experiments involved using the radars to measure the distance or movement of objects. For example, one group of students measured how a ball moved traveling down a staircase, and another measured how fast a dog's tail wagged as different people the dog knew came home.

At the end of the program, students presented their final group projects to Laboratory personnel as well as families, friends, and peers to showcase what they had learned.

LLRISE: TEXAS ALLIANCE FOR MINORITIES IN ENGINEERING (TAME)

TAME student Darian Hardin proudly displays his range radar during a Zoom presentation of his experiment and results with the radar.

In March, Lincoln Laboratory Outreach partnered with the Texas Alliance for Minorities in Engineering (TAME) to provide the LLRISE course in a virtual setting for high school students from Texas during their spring break week.

The organization offers age-specific programs to spark and support student interest in the sciences and technological careers, and provides professional development and curriculum ideas for teachers to educate families about opportunities in STEM.

Lincoln Laboratory engineers taught 27 students from all over Texas the basics of radar. Students then used scientific problem-solving strategies to experiment with a range radar that they could keep. Participants were able to perform their own experiments with Doppler radar and listen to supplemental seminars in between lectures. The course was also offered to Texas educators, who may choose to support an extracurricular radar workshop for their school.

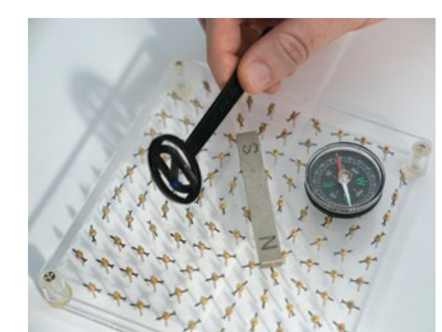
The students completing this shortened one-week workshop were encouraged to apply for the full two-week radar summer workshop, as well as the one-week cryptography program.

SCIENCE ON SATURDAY

Lincoln Laboratory's Science on Saturday series resumed in a virtual format. The topics of interest reached from outer space to Earth's own airspace and back again. The April event, Destination: Space Exploration, presented by Ariel Sandberg, investigated the missions launched in 2020 and 2021, including Perseverance and OSIRIS-REx. Participants were treated to a behind-the-scenes look at the payloads created at Lincoln Laboratory, as well as a discussion of how the Laboratory builds items to withstand the space environment.

The Aviation Today show in June featured Caroline Lamb explaining which technologies used by the National Oceanic and Atmospheric Administration (NOAA), NASA, and the U.S. Air Force trace their heritage to Lincoln Laboratory and MIT. She added descriptions of how Laboratory engineers modify aircraft to enable research. Mark Mazumder discussed the variety of ways the Autonomous Systems Development Facility at Lincoln Laboratory is used.

In October, J. Brent Parham's Space Weather talk explained how plasma and radiation emissions from the Sun can hamper satellites, communications, and electrical grids. Parham further described how and why NOAA tracks the weather in space. Participants were intrigued to see evidence of the Sun's coronal eruptions and the ways they can drastically affect systems on earth.



The Space Weather Science on Saturday presentation by J. Brent Parham showed children how solar wind variations and geomagnetic storms can penetrate our atmosphere and disrupt Earth's magnetic field, temporarily threatening spacecraft, navigation systems, and power grids.

>> *Educational Outreach, cont.*

BEAVER WORKS SUMMER INSTITUTE

This year's Beaver Works Summer Institute (BWSI) was held in a virtual format, enabling the program to include more students and more courses. Thirteen courses were offered for 351 students. The classes presented this year were Autonomous RACECAR, Autonomous Air Vehicle Racing, Autonomous Underwater Vehicle Racing Challenge, Autonomous Cognitive Assistant, Unmanned Air System–Synthetic Aperture Radar, Data Science for Health and Medicine, Build a CubeSat, Embedded Security and Hardware Hacking, Remote Sensing, Serious Game Design and Development with AI, and new classes on Cyber Security for Software Intensive Systems, Quantum Software, and Assistive Technology.

All students received either prebuilt hardware or a kit of parts so that all courses still incorporated a strong hands-on engineering experience. "Bringing the BWSI program online has helped make the course materials available to many more people than we initially imagined," said Joel Grimm, Beaver Works manager. "We have increased the number of online prerequisite courses available and created asynchronous courses for learners. It is so much more accessible than we ever thought possible."

BWSI: RACECAR IN HUNTSVILLE

Students assemble components of their autonomous mini-car prior to programming it in the Huntsville BWSI RACECAR program.

For the first time, staff at the Laboratory's field site in Huntsville, Alabama, offered a summer BWSI RACECAR program for six high school students. This program came about through the efforts of primary instructors Patrick O'Shea, Sarah Crews, and Justin Kizer, with assistance from Tom Schwab and Kim Shepard of MITRE Corporation. Throughout this four-week course, students gained experience programming in Python, working with lidar and stereoscopic depth cameras, and solving navigation and identification problems in order to teach an autonomous mini-car to respond to specific directives. In addition to learning how autonomous technology works, the students visited Aerobotix, a robotics technology company, and viewed the launch of the Blue Origin Shepard Rocket at the U.S. Space and Rocket Center. The field site teamed up with MITRE to build a racetrack to test the students' skills navigating autonomously around a challenging course. The program culminated with student presentations. Keith Henderlong, Huntsville Field Site lead, said, "I have no doubt this STEM outreach program inspired and transformed the future for local Huntsville-area students."

High school students review program code before the final competition event that was attended by leadership from the Marshall Islands and the U.S. Army Garrison-Kwajalein Atoll.

BWSI: RACECAR IN KWAJALEIN ATOLL

BWSI sailed to the Laboratory's Kwajalein Field site in the Marshall Islands. After a month of lessons, Kwajalein high school students learned how to create code, develop algorithms, and use software to teach a mini-car navigation, mapping, and object detection. Lincoln Laboratory program instructors helped the students understand the material while Ranny Ranis translated into Marshallese. The students learned to build and program small remote-controlled vehicles to move, avoid obstacles, navigate using a visual sensor, detect objects, and maneuver through obstacles on a racetrack in an event that was well attended by teachers, parents, and children from the community, and leadership from the Marshall Islands, U.S. Army Garrison-Kwajalein Atoll, and the Ronald Reagan Ballistic Missile Defense Test Site. "RACECAR provided opportunities for students to develop prototyping skills while exploring autonomous machine learning," said Willis. "Plus, it's just fun driving mini-cars around."

Community Giving

DONATION DRIVES

Bedford Veterans Affairs Medical Center

Santo Lucente created a year-round clothing donation drive for local veterans residing at the Bedford Veterans Affairs Medical Center. Lucente, a member of the Lincoln Laboratory Veterans' Network, said, "The Bedford Center has facilities for homeless veterans, who need all the basic necessities when they arrive. As a veteran myself, I want to do my part in helping them get what they need."

Santo Lucente and Marilyn Rosado donate boxes of new clothing for veterans to personnel from the Bedford Veterans Affairs Medical Center in Bedford, Massachusetts.

Boston Medical Center

Christopher Gibbons started a clothing and toy drive in October to benefit Boston Medical Center's clothing bank and their Child Life program. Donations to the clothing bank are given to patients in need, while the Child Life program collects small toys for in-patient kids. This in-kind donation program at Boston Medical Center is an efficient way to distribute the generosity of the Laboratory community to those most in need of support.

GAINING GROUND FARM

The Health & Wellness subcommittee organized two volunteer work sessions at Gaining Ground Farm this year: one on June 5 and another on September 11. Laboratory volunteers harvested 3,000 pounds of squash and cleared a field for a cover crop. They also received a grant from the MIT Community Giving Fund, enabling them to give a $500 donation to Gaining Ground Farm, which grows food for organizations that assist those experiencing food insecurity.

Laboratory volunteers harvest butternut squash for delivery to local food banks.

STOP HATE COMMUNITY BAKE SALE

Victoria Helus organized a series of bake sales to combat hate against minorities. While most bake sales disappeared during the pandemic, Helus cleverly produced a menu of bakery items to pre-order, baked the requested items, and offered touch-free delivery/pick-up. She raised $1,030 in June 2020 and donated it equally among the American Civil Liberties Union, the Innocence Project, and Black Women's Blueprint. In March 2021, she repeated the effort and raised $1,200, splitting the proceeds equally between Stop Asian American Pacific Islander Hate, the Asian American Legal Defense Fund, and the Asian Pacific Fund.

ALZHEIMER'S AWARENESS AND OUTREACH

Walk to End Alzheimer's

This year, Lincoln Laboratory celebrated its 13th anniversary of participating in the Walk to End Alzheimer's. The walk took place in a virtual setting on September 26. The 11 team members walked individually on sidewalks, tracks, and trails to participate in this year's walk and raised $24,770 of their $30,000 goal.

Ride to End Alzheimer's

For the tenth year, the Alzheimer's Support Community invited cyclists to join the 2021 Ride to End Alzheimer's in Rye, New Hampshire. This year's team raised $22,600, surpassing their goal of $20,000 and ranking them the fourth-highest fundraising team in the region.

GOVERNANCE AND ORGANIZATION 99

Laboratory Governance and Organization

MIT

Dr. L. Rafael Reif
President

Dr. Martin A. Schmidt
Provost

Dr. Maria T. Zuber
Vice President for Research

DoD Joint Advisory Committee

The committee annually reviews the Laboratory's proposal for programs to be undertaken in the subsequent fiscal year and five-year plan.

Dr. Jagadeesh Pamulapati, Acting Chair
Director, Defense Laboratories Office

Mr. Douglas R. Bush
Acting Assistant Secretary of the Army for Acquisition, Logistics, and Technology

Ms. Darlene Costello
Acting Assistant Secretary of the Air Force for Acquisition, Technology, and Logistics

Vice Admiral Jon A. Hill
Director, Missile Defense Agency

Brigadier General Heather L. Pringle
Commander, Air Force Research Laboratory

Dr. Christopher Scolese
Director, National Reconnaissance Office

Mr. Frederick J. Stefany
Assistant Secretary of the Navy for Research, Development, and Acquisition

Dr. Stefanie Tompkins
Director, Defense Advanced Research Projects Agency

Ms. Kathy L. Watern
Executive Director, Air Force Life Cycle Management Center

Lincoln Laboratory

Eric D. Evans
Director

Justin J. Brooke
Assistant Director

Melissa G. Choi
Assistant Director

C. Scott Anderson
Assistant Director – Operations

Heidi C. Perry
Chief Technology Officer

Bernadette Johnson
Chief Technology Ventures Officer

Israel Soibelman
Chief Strategy Officer

Chevalier P. Cleaves
Chief Diversity and Inclusion Officer

Robert D. Loynd
Executive Officer and Chief of Staff

Office of the Director

David Suski
Ethics and Compliance Assurance Office

Brian O. Primeau
Environmental Health and Safety

J. Michael Menadue
Capital Projects

Daniel M. Marcus
Mission Assurance

Jacob M. Williams
Program Management

Dennis A. Burianek
Business Transformation

David Culbertson
Flight Test Facility

David R. Granchelli
Communications and Community Outreach

Service Departments

Donald L. Vandeveer
Contracting Services

Joseph Dolan
Facility Services

Patricia O'Riordan
Financial Services

Kerry A. Harrison
Human Resources

Robert D. Solis
Information Services

James A. Kennedy
Chief Security Officer

Advanced Technology

Robert G. Atkins
Head

Craig L. Keast
Associate Head

Mark A. Gouker
Assistant Head

Air, Missile, and Maritime Defense Technology

Katherine A. Rink
Head

William J. Donnelly III
Assistant Head

Aryeh Feder
Assistant Head

Biotechnology and Human Systems

Edward C. Wack
Head

Jeffrey S. Palmer
Assistant Head

Christina M. Rudzinski
Assistant Head

Communication Systems

J. Scott Stadler
Head

James Ward
Associate Head

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Assistant Head

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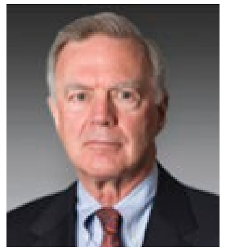

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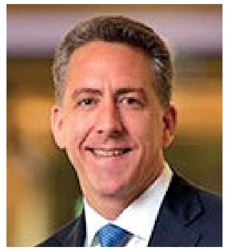

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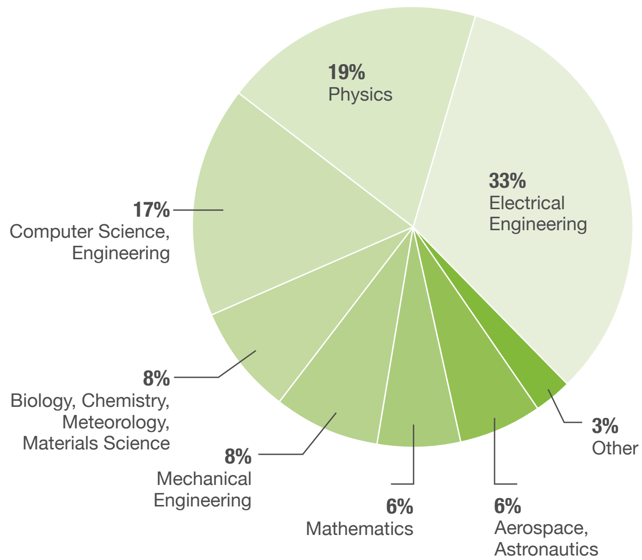
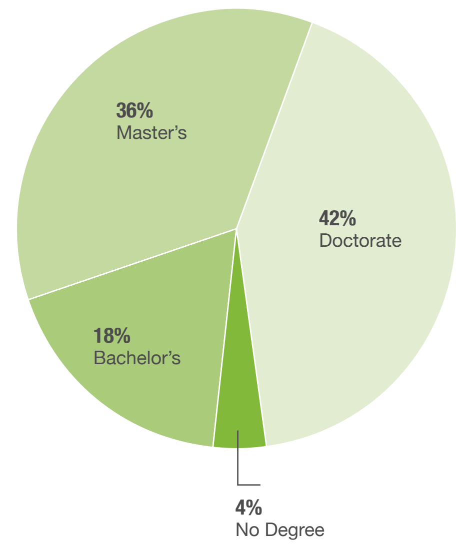
1,806	Professional Technical Staff
1,300	Support Personnel
536	Technical Support Personnel
486	Subcontractors
4,128	**Total Employees**

Composition of Professional Technical Staff

Academic Discipline

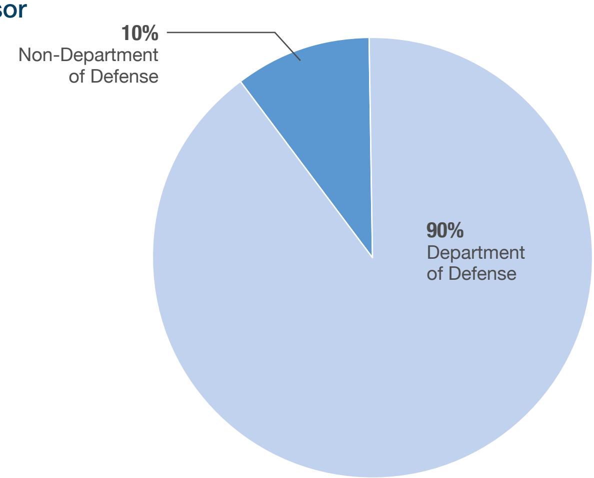


Academic Degree

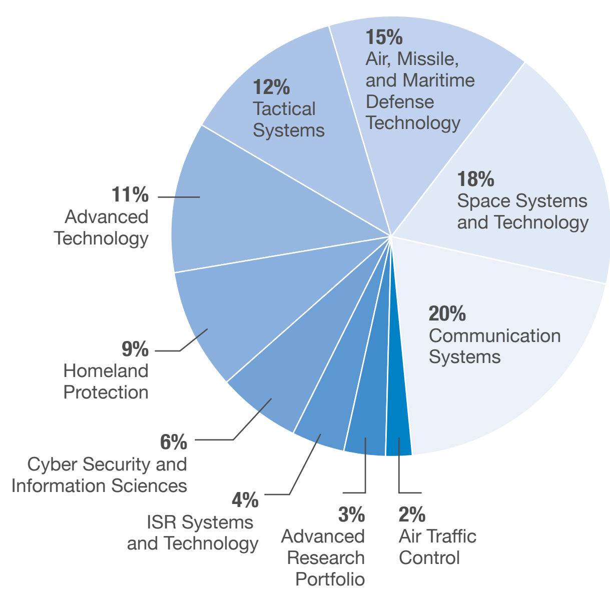


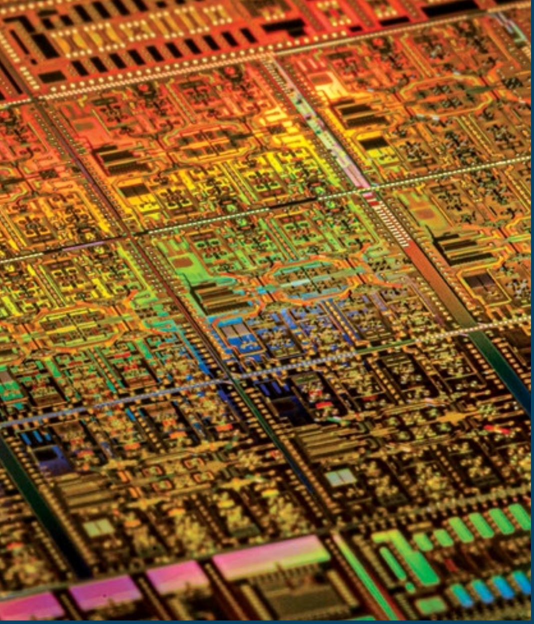
Breakdown of Laboratory Program Funding

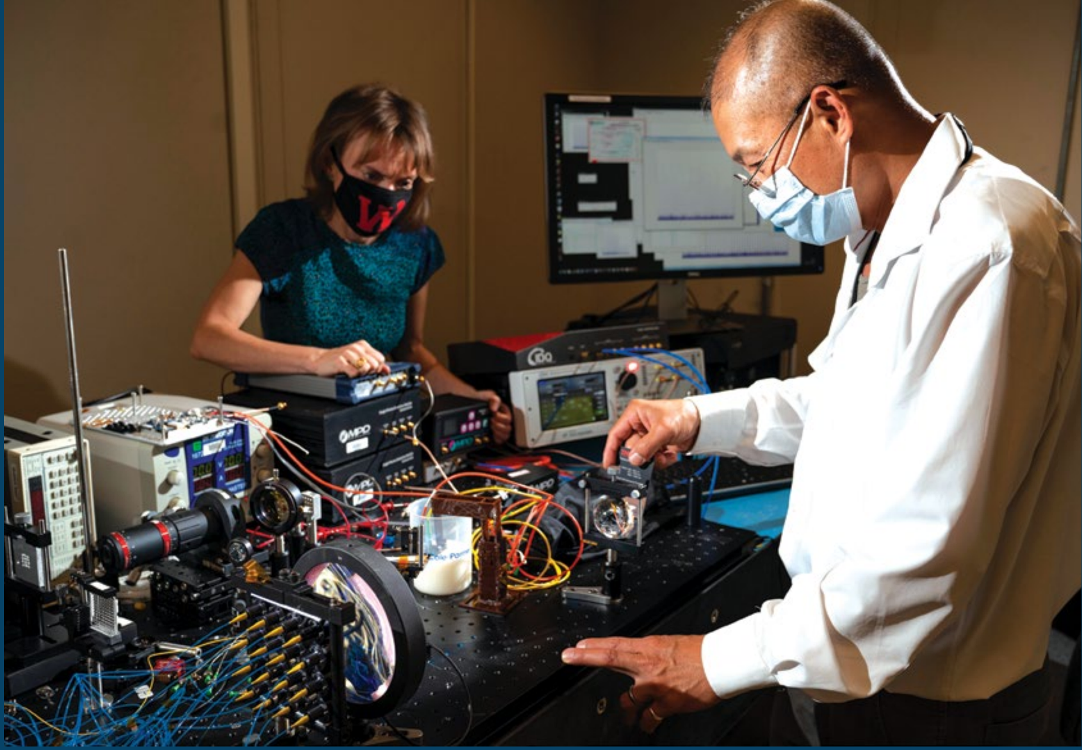
Sponsor



Mission Area







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