# Lincoln Laboratory

Lincoln Laboratory is a Department of Defense (DoD) federally funded research and development center operated by MIT. Under a prime contract with the Department of the Air Force, Lincoln Laboratory conducts research and development on behalf of the military services, the Office of the Secretary of Defense, the intelligence community, and other government agencies.

Lincoln Laboratory's mission is to develop technology in support of national security. Research and development conducted at the laboratory covers a broad range of domains, including space security; air and missile defense technology; cybersecurity; communication systems; bioengineering; maritime defense technologies; microelectronics; air traffic control; and intelligence, surveillance, and reconnaissance (ISR).

The laboratory's strengths and deep expertise in sensors and information extraction—signal processing and embedded computing—are applied to all these domains, as well as to new areas, such as energy and humanitarian assistance and disaster relief. The laboratory focuses on prototyping new technologies and capabilities to meet DoD needs that cannot be met as effectively by existing government or contractor resources.

Lincoln Laboratory researches and prototypes technologies to meet new challenges presented by the evolving needs of the nation and its military services. In the last year, the laboratory undertook programs to develop technologies that will enable undersea communications; investigated ways to harness the potential of quantum physics for enhanced computing; demonstrated a charge-coupled device fabricated on germanium; and delivered a prototype of a large, 76-panel multifunction phased array radar to the National Severe Weather Laboratory in Oklahoma.

During and after 2017's disastrous hurricane season, Lincoln Laboratory supported the Federal Emergency Management Agency's (FEMA) planning and recovery efforts. A software tool developed by the laboratory provided FEMA with weather forecasts, precipitation models, storm surge predictions, and other data analytics that helped the agency make evacuation decisions. For two weeks in September, members of the laboratory's Active Optical Systems group flew an airborne LAser Detection And Ranging (LADAR) imaging system over sites in Texas devastated by Hurricane Harvey to generate 3D views of debris piles blocking access to roads and buildings. The maps and volume estimates of the debris allowed FEMA to identify areas most in need of damage remediation.

A CubeSat carrying a miniaturized instrument developed by the laboratory was launched in January 2018 and is producing high-resolution imagery in three dimensions—latitude, longitude, and altitude—of the temperature and humidity of the Earth's atmosphere and surface.

New facilities are opening up possibilities for work in emerging cutting-edge technologies. The establishment of the Defense Fabric Discovery Center at the laboratory will enable research and development (R&D) of fibers that incorporate sensing capabilities into fabrics for soldiers' uniforms and equipment. The laboratory's new

17,000-square-foot Autonomous Systems Development Facility is being used to conduct proof-of-concept demonstrations and operational tests on small, robotic ground vehicles and unmanned aerial aircraft.

More examples of this year's R&D are presented in the technical program highlights section.

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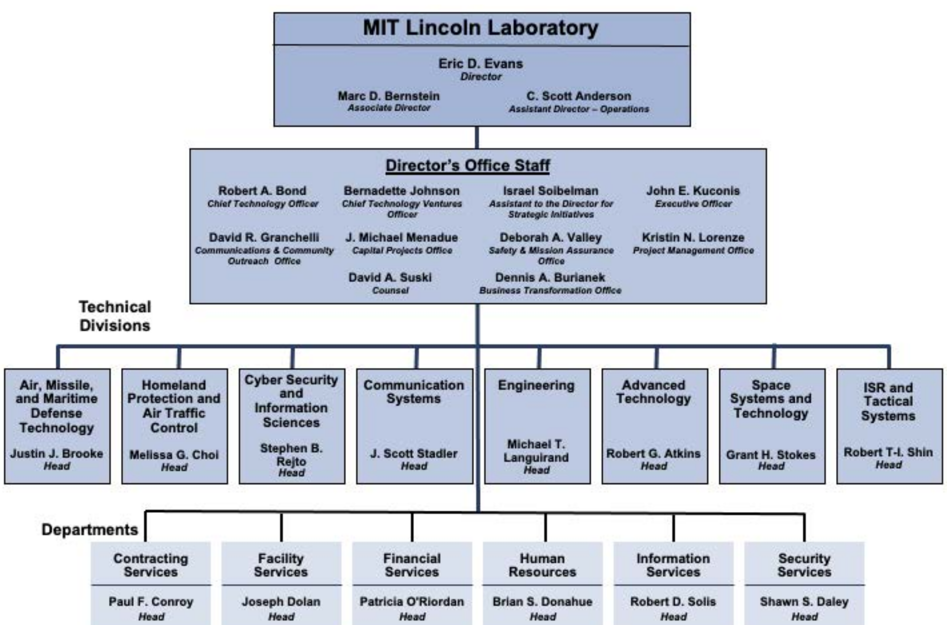
Lincoln Laboratory's fiscal year runs from October 1 to September 30. For fiscal year 2017 (October 1, 2016, to September 30, 2017), Lincoln Laboratory received approximately $1.0153 billion in total funding to execute R&D on sponsored projects. While most of the research is sponsored by the DoD, funding is also received from the Federal Aviation Administration (FAA), the National Aeronautics and Space Administration (NASA), the Department of Homeland Security (DHS), and the National Oceanographic and Atmospheric Administration (NOAA). In addition, Lincoln Laboratory also carries out noncompetitive research with industry under approved Cooperative Research and Development Agreements and other collaborative activities with academic institutions.

## Organization

Lincoln Laboratory's three-tiered organizational structure—Director's Office, divisions and groups, and departments—encourages interaction between staff and line management. Sponsor interest in conducting research and development of more complex, integrated systems has raised the level of collaboration between divisions. Service departments provide critical administrative and infrastructure support. The Mission Assurance Office and the Program Management Office enable cross-divisional research teams to coordinate and manage the technical and programmatic challenges of large-scale developments.




*Lincoln Laboratory's organizational structure as of July 2018.*

## Leadership Changes

### *Chief Technology Ventures Officer*

Bernadette Johnson was named Lincoln Laboratory's chief technology ventures officer. She will be responsible for developing and promoting initiatives to advance technology transfer with industry. Prior to this appointment, she served as the chief science officer at the Boston office of the DoD's Defense Innovation Unit Experimental.

### *Air, Missile, and Maritime Defense Technology Division*

William J. Donnelly was appointed assistant head of the Air, Missile, and Maritime Defense Technology Division; he previously served as an assistant head in the Space Systems and Technology Division.

### *Engineering Division*

Edwin F. David was appointed an assistant head of the Engineering Division. Prior to this appointment, he was the leader of the Homeland Protection Systems Group.

### *Space Systems and Technology Division*

D. Marshall Brenizer was appointed an assistant head of the Space Systems and Technology Division. Prior to this appointment, he served as the leader of the Space Systems Analysis and Test Group.

### *Program Management Office*

Kristin N. Lorenze was appointed the head of the new Program Management Office, which will provide a highly skilled cadre of program managers who can offer a rigorous balance of technical and management capabilities to R&D efforts. Prior to this appointment, she led the laboratory's Program Support Office.

### *Business Transformation Office*

Dennis A. Burianek was appointed to lead the newly established Business Transformation Office. This office will guide the Digital Enterprise Transformation, a broad initiative to improve the efficiency and effectiveness of Lincoln Laboratory's business operations. Prior to this appointment, he was the associate leader of the Systems Engineering Group.

## Technical Program Highlights

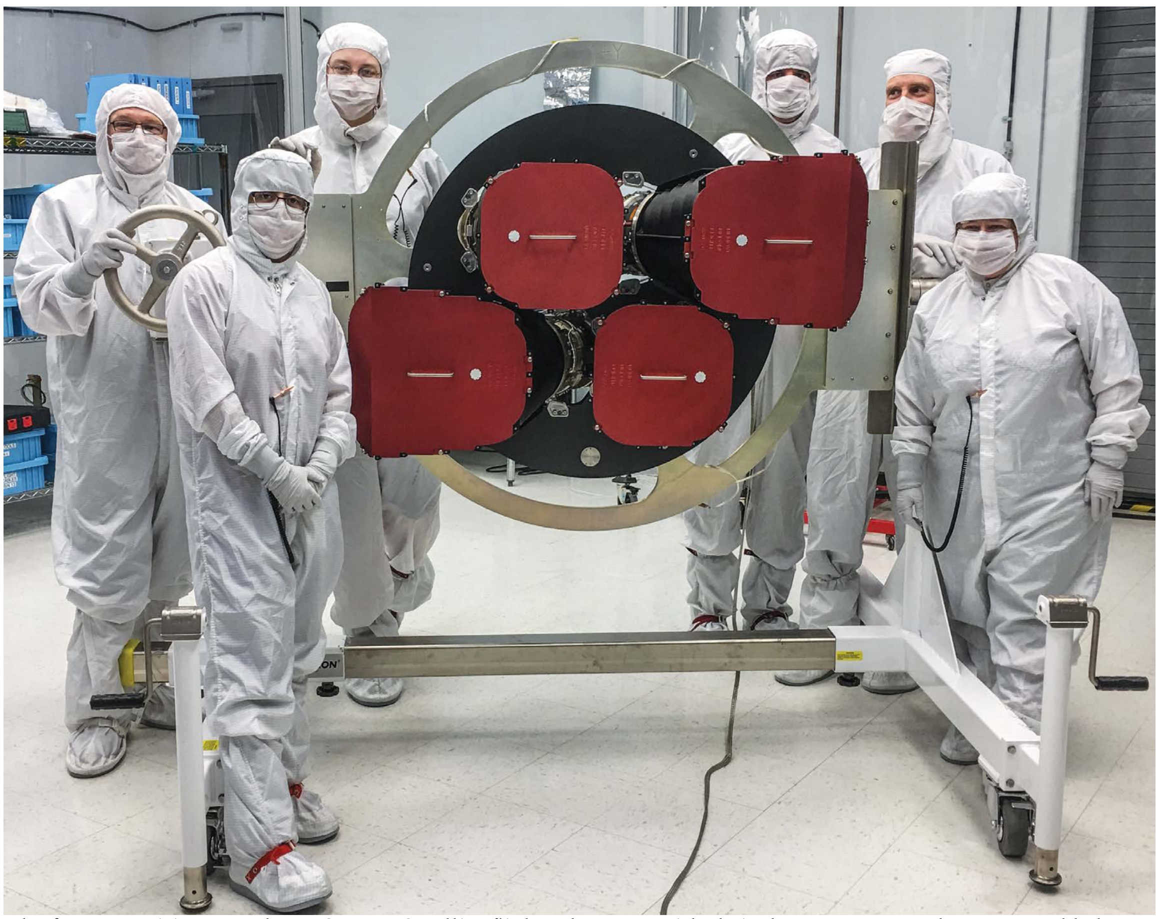
R&D at the laboratory focuses on national security problems across a broad range of mission areas: tactical and ISR systems; air, missile, and maritime defense; space security and space systems; chemical and biological defense; homeland defense; communications; cybersecurity and information sciences; and advanced electronics technology. In addition, the laboratory undertakes work in related, nondefense areas, such as air traffic control, weather sensing, and environmental monitoring. A principal activity of the laboratory's technical mission is prototyping, which involves the development of components and systems for experiments, engineering measurements, and tests under field operating conditions.

This year, Lincoln Laboratory worked on approximately 620 programs that range from large-scale hardware projects to small seedling initiatives. Notable highlights for each mission area are listed below.

## Space Systems and Technology

The Space Surveillance Telescope was disassembled at White Sands Missile Range, New Mexico, and shipped to Naval Communication Station Harold E. Holt (HEH) in Australia. The new telescope enclosure at HEH is undergoing its final preparations for installation and reassembly of the telescope.

The Transiting Exoplanet Survey Satellite flight payload, jointly developed by the MIT Kavli Institute for Astrophysics and Space Research and Lincoln Laboratory under funding from NASA, was delivered to the spacecraft vendor in preparation for an early 2018 launch.



*The four Transiting Exoplanet Survey Satellite flight telescopes with their detector arrays, shown assembled on their base plate, are ready for integration on the spacecraft. Lincoln Laboratory provided the detector arrays, optical subsystem, system engineering, integration and test, and program management for the science payload.*

The Microwave Radiometer Technology Acceleration (MiRaTA) CubeSat, a development between MIT Space Systems Laboratory and Lincoln Laboratory that is funded by the NASA Earth Science Technology Office, was successfully launched and deployed on November 18, 2017. MiRaTA is undergoing in-orbit check out of the spacecraft and its multiband radiometer and GPS radio occultation payloads. The Micro-sized Microwave

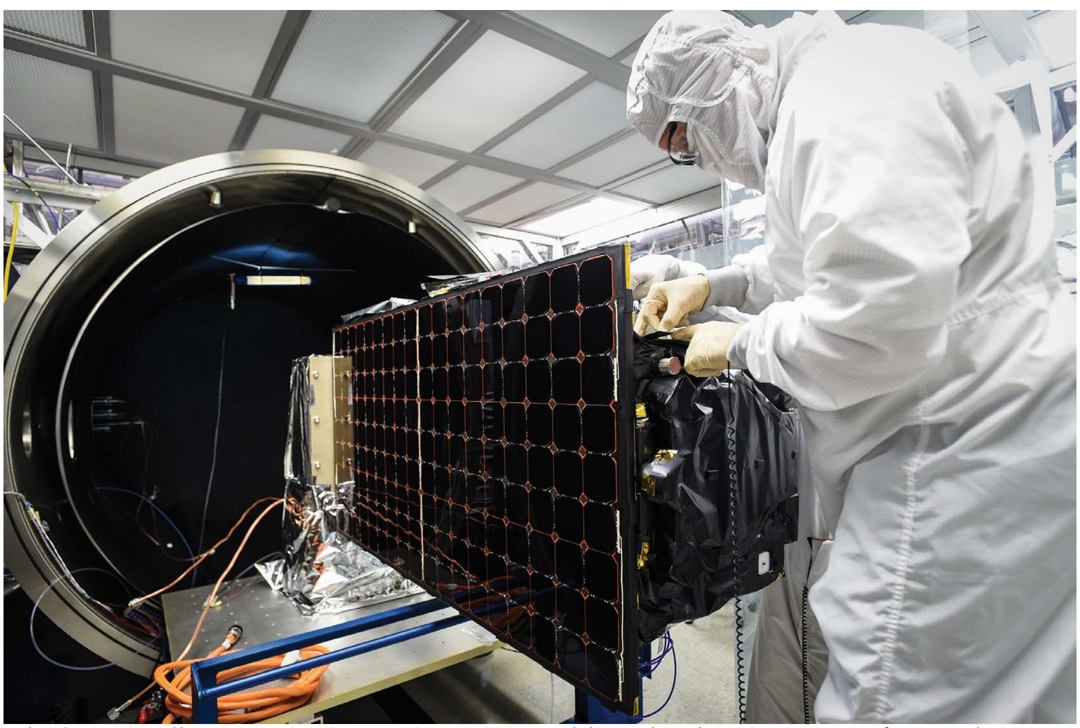
Atmospheric Satellite-2a (MicroMAS-2a) CubeSat passed qualification testing and was delivered to the launch provider in anticipation of a launch in early 2018.

Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS), a NASA Earth Venture-Instrument program, is a constellation of CubeSats equipped with advanced compact microwave sounder technology to provide high-revisit observations of precipitation, temperature, and humidity in tropical storms. The TROPICS System Requirements Review was successfully completed, and design work is underway.

The laboratory is designing a distributed radar prototype for deep space surveillance. An exhaustive trade study examining the operating frequency, antenna quantity and size, and array configuration was conducted to determine the most cost-effective radar that meets mission objectives.

A portfolio of activities continues to deliver critical space domain awareness information and tools to the National Space Defense Center in Colorado.

SensorSat is a small satellite developed for the Operationally Responsive Space Office to meet a US Strategic Command need in space situational awareness. SensorSat's use of a particular orbit exploits sensor viewing angles to reduce the apparent motion of targets and substantially increase detection sensitivity. This approach, which uses a small aperture, provides a substantial reduction in spacecraft complexity, size, mass, and cost. SensorSat, launched on August 26, 2017 from Cape Canaveral, FL, on a Minotaur IV vehicle, underwent a successful vehicle and system check out. SensorSat will be a contributing sensor to the Space Surveillance Network in early 2018.



*The Operationally Responsive Space-5 SensorSat was delivered to the US Air Force after completion of testing to verify the hardware-to-software interfaces, vibration testing to replicate the launch environment, and performance testing in a thermal-vacuum chamber to simulate the space environment.*

## Air, Missile, and Maritime Defense Technology

Lincoln Laboratory is at the forefront of appraising the impact of rapidly evolving missile threats on Ballistic Missile Defense System (BMDS) performance. As Technical Direction Agent for the homeland defense system, the laboratory is conducting system-level analyses of Ground-Based Midcourse Defense performance and is leading efforts to identify and develop system improvements to mitigate the impacts of these evolving threats.

Design and development continued on flight test countermeasures that are used for evaluating the performance of the BMDS and its elements.

Critical prototypes that were developed to explore new capabilities for future airborne sensors include a next-generation radar test bed to prototype waveforms and algorithms, and a wideband phased array for airborne testing and evaluation.

In collaboration with MIT and Woods Hole Oceanographic Institution, the laboratory conducted a demonstration at Buzzards Bay, MA, of enhanced path planning for unmanned undersea vehicles.

*The laboratory is developing advanced technology for unmanned undersea and surface vehicles. This Maritime Autonomy Test Tank is a controlled environment in which staff can refine capabilities in autonomy, sensing, signal processing, and communications prior to open-water demonstrations.*

A highly reconfigurable multiband seeker test bed was developed to assess the performance of emerging seeker concepts and technologies.

To improve the performance of the US Navy sonar systems, the laboratory developed adaptive beamforming architectures that exploit special characteristics of underwater environments. During the ICEX16 arctic experiment, Lincoln Laboratory researchers assessed noise recorded on sensors installed on a submarine and on an unmanned undersea vehicle to demonstrate improved calibration and signal processing techniques.

System-level assessments of vulnerabilities of US undersea capabilities utilized the laboratory's expertise to inform DoD leadership of improved tactics and future system development options. The laboratory completed a major digital receiver architecture demonstration system on an existing over-the-horizon radar.

A Lincoln Laboratory research team developed the pulse-to-pulse phase diversity technique for suppressing signal interference and eliminating the ambiguity in range measurements that is inherent in pulse-Doppler radar. The technique uses a specialized radar transmit waveform and a tailored chain of signal processing algorithms to eliminate range ambiguity and filter out interference, such as ground clutter and wind turbine effects.

### Communication Systems

- During an operational flight exercise, Lincoln Laboratory demonstrated the use of real-time adaptive beamforming to provide enhanced jamming resistance to airborne tactical data links.
- The laboratory used protected military satellite communication terminals to define and demonstrate a method for local time transfer.
- Flight-testing of an initial production satellite communications terminal with an airborne antenna was conducted for the Family of Advanced Beyond Line-of-Sight Terminals (FAB-T), which will help to move large amounts of information to and from ground installations and airborne platforms.
- An acquisition detector array is under development for robust laser communication (lasercom) beam acquisition. A prototype device with the capability to differentiate multiple inputs and acquire and track the signal of interest was demonstrated.
- A concept was developed for a next-generation, low-size, low-weight, and low-power airborne lasercom terminal that enables high-data-rate communication over a wide field of regard.
- To validate the pointing, acquisition, tracking, and communication performance and interoperability among lasercom terminals, Lincoln Laboratory developed multiple test beds.
- The laboratory implemented a configurable composable architecture for airborne tactical data links. The architecture was used to instantiate all major airborne DoD waveforms and will simplify the development and deployment of future waveforms.
- For a prototype third-generation space lasercom beam director, prototype gimbal and telescope subassemblies delivered by contractors were integrated with a small optics assembly developed at Lincoln Laboratory.

Lincoln Laboratory demonstrated the first-ever distributed coherent transmit radio system for low-probability-of-detection anti-jam communications. The Computational Leverage Against Surveillance Systems mobile radios cooperatively focus a message transmission on the base station to increase the received power by the square of the number of mobile radios. This cooperative radio arrangement results in an increase in throughput, a reduction in battery size, and a range extension to maneuvering squads of soldiers. This system was developed with funding from the Defense Advanced Research Projects Agency (DARPA).

*Researchers demonstrate the Computational Leverage Against Surveillance Systems mobile radios in the field.*

## Cybersecurity and Information Sciences

The laboratory completed hands-on, in-depth cyber red team vulnerability assessments of the Joint Direct Attack Munition guidance system and the Joint Mission Planning System, both of which are used extensively by the military and are critical to warfighting effectiveness.

The Lincoln Laboratory Supercomputing Center deployed a new petaflop-scale system that consists of 41,472 processor cores and can compute 1,015 operations per second. This new system, with six times more processing power than the previous one, will enable research across all mission areas.

DHS's Cybersecurity Division selected several Lincoln Laboratory technologies for its Transition to Practice program, including tools to support cyber-defense planning, certificate distribution to the cloud, and cyber-based analysis.

For the Office of Naval Research, the laboratory developed a prototype that uses an augmented reality display to enable marines to maintain hands-on control of their weapons while they assess an adversary's cyber presence in the electromagnetic (EM) spectrum.

The laboratory provided test and evaluation support for the DARPA Cyber Grand Challenge, the first automated Capture the Flag event showcasing cyber-reasoning systems. Capture the Flag competitions challenge participants to find and mitigate computer threats.

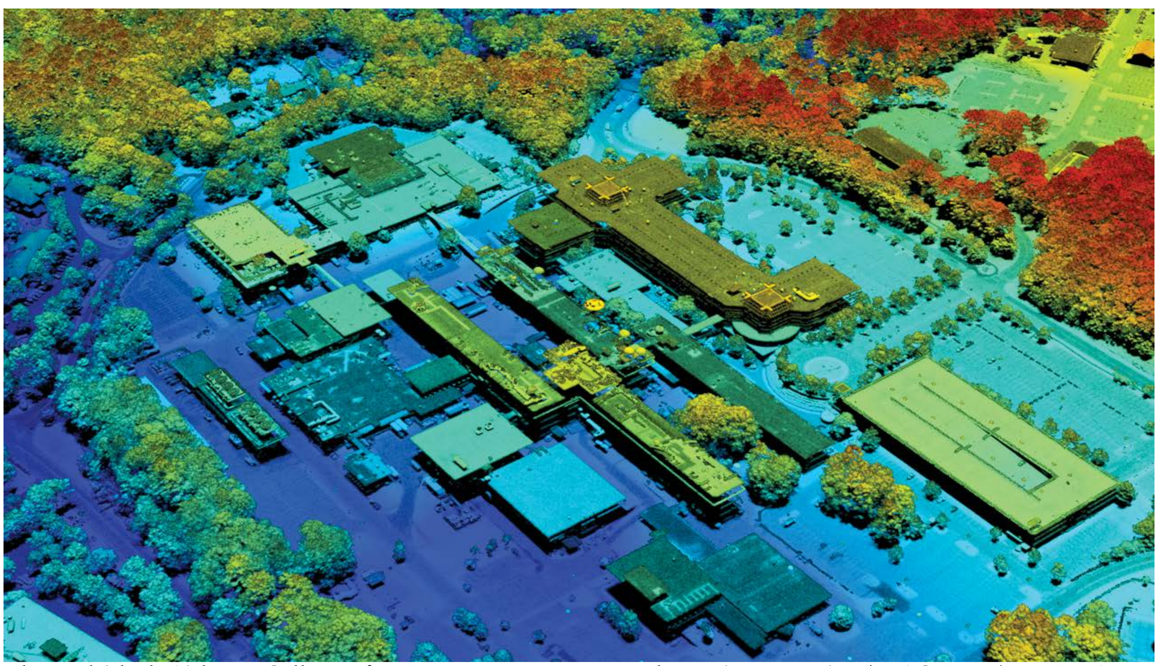
The laboratory performed technical analyses and developed three prototypes for the US Cyber Command Capabilities Development Group. The prototypes will enable joint warfighting capabilities for the Cyber Mission Forces.

A practical approach for identifying counterfeit electronics, developed and validated by researchers at Lincoln Laboratory, utilizes side-channel analysis techniques. Counterfeit microelectronics represent billions of dollars in risk to operator safety and financial loss. The Side-Channel Authenticity Discriminant Analysis was designed as a scalable, cost-effective solution to mitigate the growing counterfeit threat.

### Intelligence, Surveillance, and Reconnaissance Systems and Technology

Lincoln Laboratory provided technical analysis to support key decisions for US Air Force and US Navy acquisition programs, including the Joint Surveillance Target Attack Radar System (JSTARS) Recapitalization program. Techniques, technology, and tactics for the protection of airborne radar systems in jamming environments were developed and tested. Phenomenology experiments were conducted to characterize complex radio frequency (RF) propagation and scattering in support of advanced system concepts. The airborne radar test bed for prototyping advanced RF and processor technology is under development.

The Airborne Optical System Test Bed LADAR system was deployed to Texas in September 2017 to support post-Hurricane Harvey recovery efforts. The system generated 3D maps that provided critical infrastructure damage assessment and quantified debris volumes over city-scale areas. These capabilities are potentially game changing for disaster recovery and public assistance efforts.



*The Multi-look Airborne Collector for Human Encampment and Terrain Extraction (MACHETE), a 3D LAser Detection And Ranging (LADAR) designed to uncover clandestine activity in heavily foliated areas, employs photodiode arrays to collect and process data to create 3D images, such as the above image of Lincoln Laboratory.*

Lincoln Laboratory developed the Coherent Low-Power Adaptive Signaling System (CLASS) application-specific integrated circuit system on chip. This system enables radios to operate in spectrally congested environments and coherently transmit energy. CLASS enables multiple distributed radios to cooperate and focus their energy on a base station to achieve significant transmit power reduction, data rate improvement, and range extension.

New architectures for knowledge extraction from publicly available information continue to be developed and demonstrated. Research into network graph exploitation and deep-learning techniques emphasizes the delivery of real-time intelligence data to tactical analysts.

Lincoln Laboratory developed a prototype of a novel, ground-based infrared (IR) surveillance system. The prototype employs multiple uncooled microbolometer cameras mounted on a pan-tilt gimbal. Imagery from the cameras is processed by a custom suite of signal processing algorithms. Data collected from field tests of the system are used to assess the utility of inexpensive, commercially available IR detectors for tactical applications and to develop advanced algorithms that optimize the detectors' performance.

The Airborne Radar Test Bed (ARTB) is a flexible, open-architecture radar system well suited to demonstrate next-generation system concepts, novel algorithms, and advanced RF technology. This system will host a side-looking active electronically scanned array. The Advanced Technology Division is developing a scaled version of the Multifunction Phased Array Radar panel, which will be integrated on the ARTB in 2019 to support a wide-bandwidth fully polarimetric capability.

### Tactical Systems

Lincoln Laboratory is developing and demonstrating innovative concepts for employing micro-sized air vehicles in national security contexts. In 2016, a major flight demonstration of coordinated autonomy was achieved by the nation's largest formation of air-launched, micro air vehicles. Under the sponsorship of the Office of the Secretary of Defense, Strategic Capabilities Office, the laboratory has been exploring follow-on system and mission concepts, and conducting flight tests of the micro air systems with the US Marine Corps.

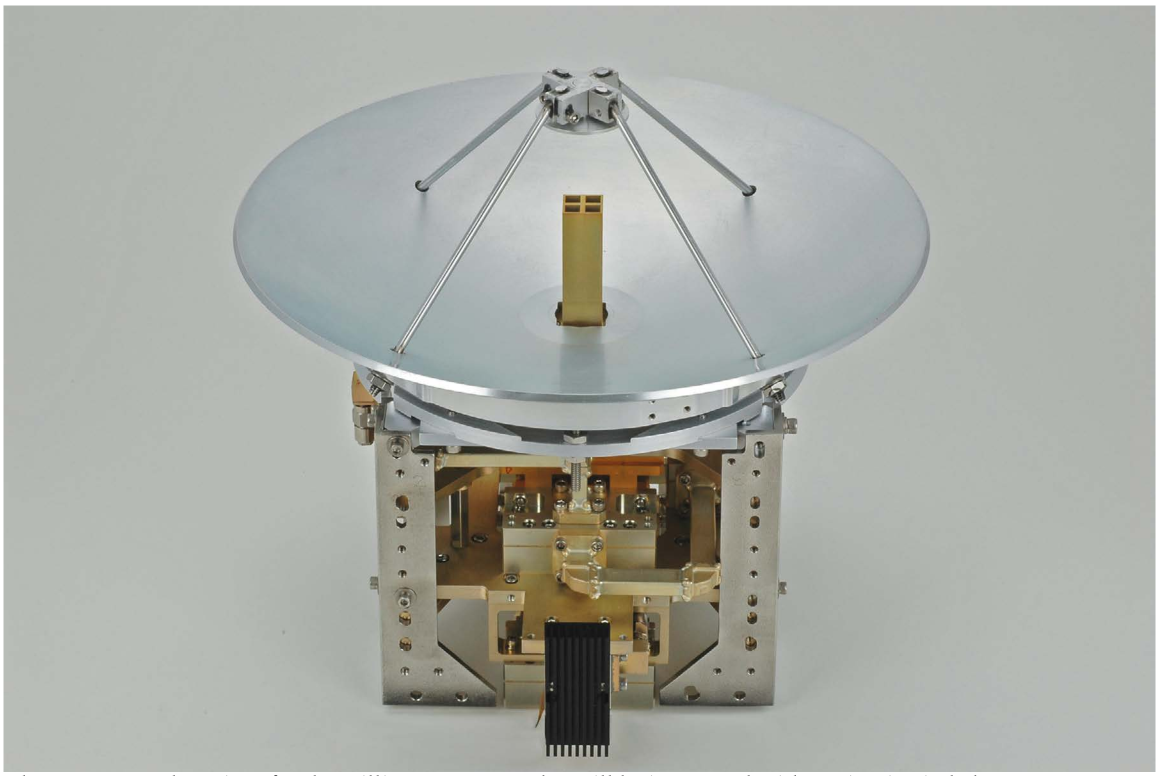
The laboratory continues to conduct system analyses, laboratory testing, and flight-system data collections that inform its assessments of the performance and limitations of air force aircraft against current and future foreign threats. These assessments—which include investigations of missile systems performance, electronic attack and electronic protection, and RF and advanced IR sensor kill chains—have been presented to DoD leadership to advise their decisions about technology investments and future system capabilities.

To evaluate the performance of various options for airborne electronic attack, the laboratory has performed systems analyses, developed detailed models, and fielded prototype threat radar systems, including systems used for surveillance, target acquisition, and fire control.

The analytical assessment of a family-of-systems architecture that involves teaming manned and unmanned aircraft has shown the potential for new operational capabilities in a contested environment. The assessment's findings have been briefed to the DoD sponsor and are influencing the development of a demonstration system for these capabilities.

The laboratory continues to develop and analyze new concepts for air dominance and for ISR. Several advanced technologies that will enable new capabilities in these areas have been identified for the Air Force. Detailed modeling and systems analyses are being performed to determine the feasibility and performance of these technologies.

Lincoln Laboratory is developing an instrumentation-quality and highly calibrated millimeter-wave (mmWave) radar system. The antenna and receiver assembly shown below will be integrated into a tri-axis gimbal for precise pointing and control. The system will be captive carried on the laboratory's test aircraft for in-flight measurements at tactically significant altitudes. The laboratory will use the system to conduct research and development in target and clutter phenomenology and in advanced electronic protection and electronic attack. The mmWave radar, which is expected to reach initial operating capability in 2018, will provide key measurements to multiple assessments of DoD systems.



*The antenna and receiver for the millimeter-wave radar will be integrated with a tri-axis gimbal.*

### Advanced Technology

Through an optical systems program funded by the assistant secretary of Defense for Research and Engineering, a multidivisional Lincoln Laboratory team developed a microscope capable of chemically identifying individual micron-sized particles. Detection of these microparticles could one day enable rapid screening for trace amounts of dangerous materials, such as explosives and chemical or biological warfare agents.

A new type of microactuator demonstrated by the laboratory borrows design and operational concepts from biological muscle and stepper motors. By integrating surface-tension forces produced by electrowetting electrodes, this actuator offers a unique combination of power, efficiency, and scalability. The current actuator's output power density of 200 watts per kilogram exceeds that of most biological muscles.

In a cross-divisional effort, researchers developed a novel system prototype that provides timely (<30 s), and accurate (<50 m) geolocation of handheld laser pointers shining up into the sky. This system was designed to provide law enforcement with information that will lead to the apprehension of the perpetrators of the increasingly frequent laser strikes aimed at commercial aircrafts.

After delivering three superwideband compressive receiver (SWCR) units to Navy sponsors in 2016, the laboratory continued to provide support to the Office of Naval Research. The SWCR was deployed for data collection missions that used both wideband pulse descriptor word generation and energy mapping.

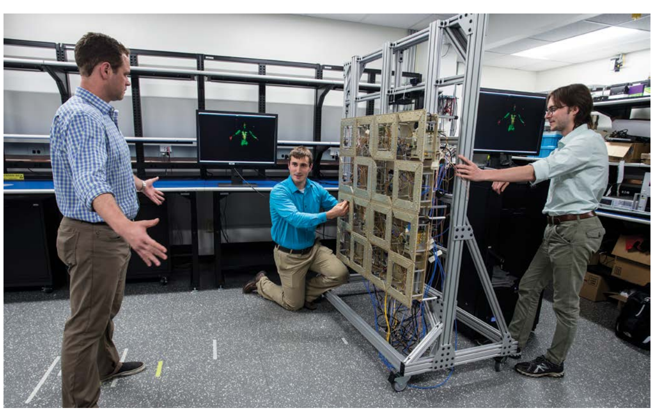
Data collected from two prototype high-frequency EM vector sensors were used to develop a maximum-likelihood processing technique that generates a map of multiple EM sources from a single EM vector sensor.

A 2 × 2 array of 4-Mpixel charge-coupled devices (CCDs) was launched aboard NASA's OSIRIS-REx satellite on a science mission to the asteroid Bennu. A 200 nm aluminum optical blocking layer is directly deposited onto the CCDs, which map elemental abundances of the asteroid via X-ray fluorescence spectroscopy.

Lead researchers from the Laser Interferometer Gravitational-Wave Observatory (LIGO) recently received the Nobel Prize in Physics for detection of gravitational radiation. The laser utilized for these discoveries was underperforming relative to design. Lincoln Laboratory staff saw an opportunity to quickly develop a new laser for LIGO that operates reliably at the desired 200W power level rather than at the current 35W level. This new laser leverages the laboratory's long-established work developing high-power fiber lasers. The system is being fully characterized on campus at MIT to investigate the feasibility of its use at the LIGO sites.

## Homeland Protection

Under DHS sponsorship, Lincoln Laboratory conducted initial experiments on "screening at speed" sensing technologies to be used at airports and other potential venues. These technologies seek to automatically detect concealed threat materials without unnecessarily restricting passenger flows. The signal processing experiments included combining advancements in low-power radar technology with video camera networks to identify regions of interest and reduce false alarms.



*Researchers examine a prototype standoff microwave imaging system for detecting concealed threats. This Lincoln Laboratory-developed system provides unique video-rate imaging capabilities for rapid screening of subjects (see computer displays in background).*

A test bed was established to evaluate concepts of operation and supporting technologies that help DHS counter the illegal use of small unmanned aerial vehicles.

A prototype system developed by the laboratory to detect, track, and classify boats using video cameras began operating in a region of the nation’s waterway borders.

In collaboration with the Joint Improvised-Threat Defeat Organization, the laboratory is transitioning the first fieldable, homemade explosives sourcing and human DNA mixture identification toolkit.

The laboratory developed the world’s fastest computational methods for searching DNA databases for human identification and forensics applications.

The Sensorimotor Technology Realization in Immersive Virtual Environments (STRIVE) Center now operates as a DoD-wide nexus for collaboration on the development of next-generation medical and operational technology and for advanced training research. Recent work at the STRIVE Center includes assessing mild traumatic brain injury with clinical and operational experimentation, developing assistive devices for people with injuries or disabilities, and evaluating tools for the assessment of musculoskeletal injury.

*The Sensorimotor Technology Realization in Immersive Virtual Environments Center enables the assessment of cognitive and physiological performance as a person interacts with a virtual environment. The researcher above is monitoring the person’s performance.*

Lincoln Laboratory is developing new tools and capabilities that improve and accelerate R&D into the human microbiome, the trillions of microorganisms residing on or in the body. One such tool is the 3D-printed, multiplexed Artificial Gut (ArtGut), which emulates key aspects of the gut, the primary environment of the microbiome. The ArtGut is composed of an array of tubes that have innovative 3D-printed spline injectors at the input end and sampling ports at the output end. The injectors allow multiple test agents, such as probiotics or toxicants, to be introduced into the ArtGut and later sampled downstream without disturbing the culture environment.

### Air Traffic Control

Development work continued on a 76-panel Multifunction Phased Array Radar prototype. In partnership with the FAA and NOAA, the laboratory established the array panel firmware and software to control and process beam-steering commands from the radar signal processor.

In partnership with the FAA and industry partners, the laboratory conducted operational test and evaluation of the Airborne Collision Avoidance System Xa (ACAS Xa), which will support new flight procedures and aircraft classes. Additionally, the laboratory led planning for the second developmental flight test of the ACAS Xu system for unmanned aircrafts.

*The control tower simulation facility serves as a test bed for evaluating new procedures and technologies that have been developed to improve airport ground operations. Researchers use realistic flight data in their proof-of-concept demonstrations.*

Algorithm improvements continued for the Offshore Precipitation Capability (OPC), which uses lightning, satellite, and meteorological model data to generate a global, radar-like view of convective weather that is beyond the coverage of land-based radars. The laboratory will expand the OPC domain and utilize data from the recently launched Geostationary Operational Environmental Satellite.

Analyses are being conducted to guide the FAA on wind information needs, particularly for four-dimensional, trajectory-based operations, for Next Generation Air Transportation System applications that are aimed at modernizing the way the National Airspace System is managed. The laboratory is assessing the utility of aircraft-derived measurements to expand the nation's wind-sensing network.

Operational improvements are being developed to mitigate the environmental impacts of aviation. The laboratory is developing techniques and procedures to reduce taxiway congestion and to select efficient aircraft altitudes and speeds.

The Small Airport Surveillance Sensor prototype demonstrated passive, real-time surface surveillance for transponder-equipped aircraft and achieved 30-foot accuracy.

Lincoln Laboratory led the development of a prototype Runway Status Light (RWSL) system that automatically warns pilots of potentially hazardous airport surface operations. After successful operational evaluations at international airports in Boston, Dallas/Fort Worth, Los Angeles, and San Diego, the RWSL technology was transitioned to industry and is now operational at 17 airports across the United States. Studies showed that RWSL can reduce serious runway incursions by up to 70%, significantly improving safety at busy airports. The last of the prototypes (at Boston, Dallas/Fort Worth, and San Diego) are scheduled to be replaced with production systems within two years.

### Engineering

Lincoln Laboratory developed a controller hardware-in-the-loop system that provides real-time simulation of distribution power grids with a variety of energy resources. It was the demonstration platform at the Microgrid and Distributed Energy Resource Controller Symposium, which the laboratory co-hosted with the Massachusetts Clean Energy Center in February 2017.

A methodology was developed to enable the design of freeform optics for the first time. Freeform optics offer significantly improved optical resolution and lower system size and weight. The laboratory built and demonstrated the nation's first spline-based, freeform telescope—a three-mirror system utilizing 6-inch optics.

The laboratory continues to set records for the brightness of beam-combined fiber lasers. This brightness has been possible, in part, because of the development of cooling systems using additively manufactured metal heat exchangers with complex internal flow geometries. The heat exchangers also provide structural support, greatly reducing the size and weight of the lasers.

Advanced semiconductor devices, such as gallium nitride transistors, are enabling new capabilities for radars and other electronic systems, but their performance is quickly being limited by the inability to reject heat. The laboratory has demonstrated a new technique using embedded microjets to cool individual devices.

Advances in unmanned aerial vehicles (UAVs) have provided the laboratory with opportunities to field a variety of sensors. The laboratory has been exploring a new concept called electro-aerodynamic propulsion to minimize the UAVs' audible signature. A UAV with a 6-foot wingspan was successfully flown under electro-aerodynamic power.

Autonomous systems employ complex autonomy algorithms with nondeterministic and adaptive behaviors that challenge traditional verification and validation approaches. The laboratory developed new algorithm techniques that were applied to a mobile manipulation task in order to avoid dynamically unstable robot configurations.

The laboratory delivered to the US Navy two Protected Aerial Contested-Environment Communications Relay (PACECR) airborne pods. PACECR is part of the Joint Aerial Layer Network–Maritime demonstration to prove the utility of aerial layers for providing critical communications in contested areas. Each pod's six subsystems were individually qualified for the demanding airborne and thermal environment. Integrating capabilities into the pod required the development of a complex power-distribution system and specialized support equipment to handle assembly and transport.

## Technology Transfer

The culmination of many of Lincoln Laboratory's development projects is the transfer of technology to government agencies, industry, or academia. The mechanisms for this transfer include the licensing of patents; delivery of hardware, software, algorithms, or advanced architecture concepts to government contractors under the auspices of a government sponsor; Small Business Technology Transfer projects, which are joint research partnerships with small businesses; and Cooperative Research and Development Agreements, which are privately funded by businesses to transfer the laboratory's technology.

### Patents

Between July 1, 2017, and June 30, 2018, 37 US patents were granted to MIT for technologies developed by Lincoln Laboratory technical staff. These patents span a wide range of technologies. Some unique technical advances that were patented are the EXtreme Virtual Memory, which is a method and computer program that together handle the distribution and management of parallel data on a hierarchical storage system; Systems, Methods, and Apparatus for Sensitive Thermal Imaging, which use the temperature sensitivity of liquid crystal birefringence to convert IR images to visible images; Phonologically-Based Biomarkers for Major Depressive Disorder, which use signals from processed speech to assess the potential of a person's suffering from depression; and Method and Apparatus for Locating a Target Using an Autonomous Unmanned Aerial Vehicle, which exploit sensor data acquired by a UAV to statistically minimize the time to autonomously locate an RF target on the ground.

### 2017 Research and Development 100 Awards

Lincoln Laboratory innovations in air traffic safety, bioengineering, ground surveillance, and radar technology earned R&D 100 Awards in 2017. The six winning technologies were developed either solely by Lincoln Laboratory researchers or collaboratively with scientists from partner organizations. Presented annually since 1962, the R&D 100 Awards recognize the 100 technology products judged by a panel of *R&D Magazine* editors and outside experts to be the most significant new developments of the year.

The winning technologies include two that could change approaches to health care. The Carbon Dioxide/Oxygen Breath and Respiration Analyzer is a system that uses data from a breath sensor to estimate how much of a person's metabolic energy is attributed to the body's burning of carbohydrates or fat. Researchers from Lincoln Laboratory, the US Army Medical Research Institute of Infectious Diseases, and the National Institutes of Health–Integrated Research Facility developed PRE-symptomatic Agent Exposure Detection, an algorithm that correlates data from wearable sensors, such as a heart rate monitor, to predict if a person has been exposed to a disease-causing pathogen even before the person exhibits symptoms.

Two winners are techniques that offer novel methods for reducing the effects of radar clutter. Polarimetric Co-location Layering mitigates the interference to maritime radar returns caused by the movement of the sea surface, and Pulse-to-Pulse Phase Diversity is an approach to suppressing several types of interference, such as that from wind turbines.

The Ground-Based Sense-and-Avoid (GBSAA) System for Unmanned Aircraft Systems enables unmanned aircraft to see and avoid other aircraft. The system meets federal standards for air traffic safety and may help expedite the acceptance of unmanned aircraft into the national airspace.

The sixth winner is the Wide-Area Infrared System for Persistent Surveillance, a tower-mounted optical system that provides 24-hour surveillance of a broad area.

## Technology Transfer Activities

During the past year, Lincoln Laboratory transitioned several technologies to industry or to government sponsors.

### *Air, Missile, and Maritime Defense Technology*

Lincoln Laboratory transitioned electronic protection technology to the prime contractor for the Airborne Warning and Control System Modernization Program.

The laboratory successfully completed the technology transfer of mature and previously flight-tested countermeasure designs to a selected industry partner for the development and delivery of flight units for an upcoming BMDS test in 2018.

### *Air Traffic Control*

The laboratory completed the development of a GBSAA system in partnership with the Department of Defense and is transitioning the system to US Army and US Air Force sites. This transition will enable the first general-purpose, sense-and-avoid system for unmanned aircraft in the National Airspace System. To date, four systems are operating in the National Airspace System, and at least two more systems will follow.

### *Cybersecurity and Information Sciences*

Speech and language recognition technology components developed by Lincoln Laboratory were transferred into key sponsor systems. These components enabled systems that demonstrated exceptional performance at international speech and language recognition evaluations conducted by NIST to measure the state of the art in human language technology and to identify the most promising algorithmic approaches to speech and language recognition.

Working with colleagues from MIT, Lincoln Laboratory researchers released an open source polystore database, BigDAWG, that can be used for managing complex and heterogeneous data. BigDAWG is available at the BigDAWG Polystore website.

### *Communication Systems*

Lincoln Laboratory released the Group Centric Networking codebase and the Dynamic Link Exchange Protocol implementation as open source software.

The fifth-generation Advanced Training Waveform, which supports the US Air Force's live, virtual, and constructive training environments, was transferred to government and industry.

The laboratory transitioned designs for the Next-Generation Laser Communications terminals to industry partners. The industry-fabricated telescope, gimbal, and latch subassemblies were integrated into a prototype terminal.

Modem and optical terminal technology have been transferred to NASA to support the development of the lasercom terminal for the Laser Communications Relay Demonstration. The laboratory worked with multiple industry vendors to validate the subsystems that NASA will use for the terminal.

### *Homeland Protection*

Through a partnership with the US Army Medical Research and Materiel Command to develop integrated, wearable sensors for improved monitoring of warfighter health and performance, a tactically acceptable, ultralow-power wearable physiological monitoring system was transitioned to industry partner Odic, Inc. for initial production. This successful transition led to Odic's being recognized by the US Small Business Administration as the 2017 Small Business Association Subcontractor of the Year for the New England Region.

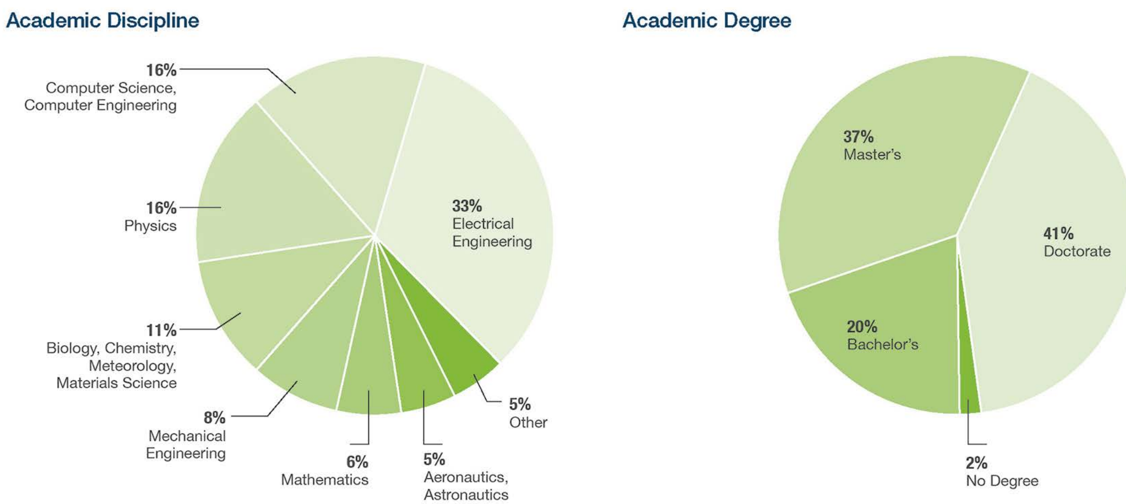
Lincoln Laboratory transitioned the HURREVAC-eXtended (HV-X), a modernized decision-making platform, to FEMA. Funded by the DHS Science and Technology Directorate, HV-X has been used in recent events, such as Hurricane Matthew, to plan evacuation routes and other responses to major storms.

### *Engineering*

The Localizing Ground-Penetrating Radar (LGPR) developed by Lincoln Laboratory has been licensed to Geophysical Survey Systems, Inc. (GSSI). GSSI will build and sell the prototype LGPR systems that enable autonomous vehicles to navigate over roads by using maps of subterranean geological features such as rock formations and soil layers. Because the LGPR uses subsurface maps, it can localize a vehicle when weather conditions such as snow or heavy rain obscure the lane markings or signs and landmarks that optical systems use to orient a self-driving vehicle.

## Staff

Key to maintaining technical excellence at Lincoln Laboratory is its staff of highly talented scientists and engineers. Of the laboratory's new professional technical staff, 70% are hired directly from the nation's leading technical universities. The laboratory recruits at colleges and universities nationwide. The makeup of the Lincoln Laboratory staff by degree and academic discipline is shown below.




*Composition of professional technical staff at Lincoln Laboratory by (a) academic discipline and (b) academic degree.*

- Professional Technical Staff: 1,812
- Support Staff (including technical support personnel): 1,619
- Subcontractors: 466
- Total Laboratory Employees: 3,897

### Awards and Recognition

During the past year, several Lincoln Laboratory staff members were recognized for achievements in their fields and for their commitment to professional activities:

- Jeffrey S. Herd was named a fellow at the Institute of Electrical and Electronics Engineers (IEEE) for leadership in the development of low-cost phased array technology.
- Melissa G. Choi, head of the Homeland Protection and Air Traffic Control Division, was appointed the vice chair of the Air Force Scientific Advisory Board, which is composed of leading national experts in science, technology, and engineering to provide independent assessments of future capabilities for the US Air Force.
- Richard M. Heinrichs, assistant head of the ISR Systems and Technology Division, was named a 2018 Military Sensing Symposia Fellow for a body of technical work that has made an outstanding contribution to military sensing.

- The 2017 MIT Lincoln Laboratory Technical Excellence Awards were presented to Gregory D. Berthiaume, for 25 years of outstanding technical contributions to the development, integration, test, and operations of space and ground-based systems that range from the soft X-ray through the thermal infrared; and Jeffrey S. Herd, for sustained innovation of radar antennas and advanced, highly digitized phased arrays, and for his leadership in building a world-class enterprise for the development of RF technology at MIT Lincoln Laboratory.
- The 2017 MIT Lincoln Laboratory Early Career Technical Achievement Awards were presented to Lori D. Layne, for her significant contributions in the development of algorithms and architectures for ballistic missile defense and for applying novel concepts in graphical networks and optimization techniques to sensor discrimination and weapon scheduling for the Ballistic Missile Defense System; and Alexander (Sasha) M. Stolyarov, for his pioneering work in the research and development of advanced functional fibers and for his outstanding leadership in nucleating and growing a new field of multifunctional fiber device technology as a core MIT Lincoln Laboratory competency area.
- Brian F. Aull, Erik K. Duerr, Jonathan P. Frechette, K. Alexander McIntosh, Daniel R. Schuette, and Richard D. Younger were presented with the 2017 MIT Lincoln Laboratory Best Paper Award for "Large-Format Geiger-Mode Avalanche Photodiode Arrays and Readout Circuits," published in *IEEE Journal of Selected Topics in Quantum Electronics*, March–April 2018.
- Peter Grossmann, Jonathan P. Frechette, Brian M. Tyrrell, Matthew S. Stamplis, and Kate E. Thurmer were presented with a 2017 MIT Lincoln Laboratory Best Invention Award for the invention of the Field-Programmable Imaging Array; and Thomas Sebastian and Christopher Strem also received a 2017 MIT Lincoln Laboratory Best Invention Award for the Toroidal Propeller.
- Christina L. Epstein was named by the Armed Forces Communications and Electronics Association International to its annual list of 40 individuals under the age of 40 who have shown exceptional leadership and innovative use of information technology to advance scientific and engineering work at their organizations.
- Alexa C. Aguilar was selected by Aviation Week Network as one of its 20 Twenties, an annual recognition of 20 engineers in their 20s whom the network, in partnership with the American Institute of Aeronautics and Astronautics, identified as having already made significant contributions to research and innovation in engineering, math, and science.
- Celeste A. Paquette and David A. Shumsky received 2018 MIT Lincoln Laboratory Administrative Excellence Awards, and Colleen D. Campbell and Kirsten L. Theophelakes received 2018 MIT Lincoln Laboratory Support Excellence Awards.
- The 2018 MIT Excellence Award for Advancing Inclusion and Global Perspectives was awarded to the Lincoln Laboratory Out Professional Employee Network (OPEN) Committee. Committee members and award recipients are as follows: Christa N. Frey, Amna Greaves, Diana B. Hanson, Alexandra C. Karlicek, Noel Keating, Ekaterina R. Kononov, Michael C. Kotson, Joel A. Kurucar, Peter E. LiBoissonnault, Mark A. Rabe, Raul Rios, Mi-Young Park Schue, and Kristi H. Wakeham

- Bobby J. Pelletier and Sarah R. Chmielewski received the Bringing Out the Best Award.
- Steven R. Holland received the Innovative Solutions Award.
- Matthew Alt, Sandra J. Deneault, and Andre J. King received the Outstanding Contributor Award.
- Adam M. Henneberry and Madeleine R. H. Riley received the Serving the Client Award.
- Derek S. Straub was chosen by the Society of Manufacturing Engineers as one of 30 people younger than 30 years old who have demonstrated exceptional engineering skills that will lead to their making outstanding contributions to the manufacturing industry.
- At their annual event, the National Fire Control Symposium recognized the research contributions of young members of the fire control community. For their presentations of their work, Matthew Gombolay earned a first-place award, and Olivia M. Brown earned a third-place award.
- Don M. Boroson, Farzana I. Khatri, Bryan S. Robinson, and Tina Shih, as members of the Orion Optical Communications Study Team, were recognized with a 2017 NASA Robert H. Goddard Award for Exceptional Achievement in Mission and Enabling Support for the team's persistence in evolving and implementing enhanced communications technologies and advancing critical mission support.
- The newly established Lincoln Laboratory Cultural Awards were given to three individuals: Keith B. Doyle received the Leadership Award for Advancing Organizational Culture for his commitment to fostering inclusion; Anne Grover Vogel received the LL Infinity Award for advancing cultural awareness at the laboratory; and John E. Kuconis received the Cultural Impact Emeritus Award for his sustained efforts to promote a culturally diverse and inclusive workplace.
- The 2017 Superior Security Rating was awarded to Lincoln Laboratory's collateral security program by the US Air Force 66th Air Base Wing Information Protection Office. This is the 12th consecutive Superior rating for the laboratory.

## Professional Development

Lincoln Laboratory's commitment to the professional development of its staff is seen in the diversity of opportunities presented by the Human Resources Department's educational program. The Human Resources Department coordinates programs in graduate education, technical education, professional leadership development, and computer and software training.

For highly qualified candidates, Lincoln Laboratory offers the opportunity to apply to the Lincoln Scholars program that supports the full-time pursuit of advanced degrees. The candidates accepted into the program perform their thesis research work at the laboratory while serving as contributing members of the staff. In FY2018, 21 staff members were enrolled in the Lincoln Scholars program.

The Part-Time Graduate Studies program enables staff members to continue to work at the laboratory while earning master's degrees in fields that are relevant to laboratory mission areas or business needs. Staff members can take courses toward their degrees through universities' part-time programs that may include classes offered online or outside traditional work hours, or both. Lincoln Laboratory staff are also eligible to take courses in computer science offered at Hanscom Air Force Base by Boston University (BU). These courses, which have included ones in computer networks, cryptography, and software engineering, can be taken independently or as part of a BU certificate or master's degree program. From July 1, 2017, to June 30, 2018, 51 people participated in these programs.

The technical education program offers both short-term and semester-length courses taught by Lincoln Laboratory technical staff or by outside experts. The AY2018 schedule included the following courses: Cyber Security Fundamentals; Decision Making Under Uncertainty; Hyperspectral Imaging; Infrared Search-and-Track Applications; Mathematics of Big Data; Neural Networks; Optics for Missile Defense; Probability and Random Processes; Software Design Patterns; Space Control; Systems Analysis; Technology in Humanitarian Assistance and Disaster Relief; and Theory and Methods for Modern Graph Analysis.

The professional and leadership development program again sponsored courses in leadership techniques, project management, preparing presentations, and scientific and technical writing. Computer training in common software applications (Word, PowerPoint, Excel, Illustrator, and Photoshop, etc.), programming, and technical software (MATLAB, Simulink, VMware, etc.) is offered onsite throughout the year. A new offering this year was a tutorial on nonparametric Bayesian methods.

### Technology Office Seminars

The Technology Office directs a program of seminars presented at the laboratory by both in-house speakers and researchers from universities and industry. The seminars are chosen to reflect current and leading-edge trends in today's technology.

Highlights of the AY2018 program include the following seminars:

- "Vehicle Design and Optimization Model for On-Demand Aviation," Arthur Brown, master's degree candidate in the MIT Department of Aeronautics and Astronautics, March 19, 2018
- "Remote Sensing in Maya Archaeology: Failures, Progress, and the Lidar Revolution," Assistant Professor Thomas Garrison, Ithaca College, Department of Anthropology, February 16, 2018
- "Climate Change: Risks and Opportunities," Kerry Emanuel, MIT Lorenz Center, October 20, 2017
- "The Power of Miniaturization in Medicine," John J. and Dorothy Wilson Professor of Engineering Sangeeta Bhatia, MIT, director of the Marble Center for Cancer Nanomedicine, September 26, 2017
- "Essential Concepts of Causal Inference—A Remarkable History," Professor Emeritus Donald Rubin, Harvard, Department of Statistics, September 25, 2017

### *Advanced Technology Division Seminar Series*

The Advanced Technology Division instituted a series of seminars on topics in science and on commercial developments of new technology. Speakers come from universities and high-tech companies that are making breakthroughs in various fields.

Seminars on the following topics were given in AY2018 by the guest speakers listed below:

- Dark-matter detection, Associate Professor James Battat, Wellesley College, February 21, 2018
- Phased-arrays and transceivers for SATCOM and 5G, Professor Gabriel Rebeiz, University of California San at Diego, January 30, 2018
- Innovation in medical imaging, Christian Eusemann, vice president of collaborations at Siemens Healthineers, January 9, 2018
- Human-robot control and interaction interfaces, Associate Professor Panagiotis (Panos) Artemiadis, Arizona State University, November 3, 2017
- Quantum information processing, David Wineland, National Institute of Standards and Technology
- Atomic clock and quantum matter, Jun Ye, National Institute of Standards and Technology, and the University of Colorado, September 19, 2017
- CubeSats with lasers, Associate Professor Kerri Cahoy, MIT, September 5, 2017
- Nanotechnology, Brent Segal, Lockheed Martin, July 24, 2017
- Very large-angle optical beam detectors, Professor Philip Bos, Liquid Crystal Institute, Kent State University, July 18, 2017

## Diversity and Inclusion

The laboratory continues to foster an inclusive workplace that leverages and supports the talents and perspectives of its staff. Recruitment at a broader range of universities, programs in mentoring, employee resource groups, and flexible work options are contributing to the hiring and retaining of a more diverse workforce.

Nine employee resource groups promote an inclusive workplace by increasing awareness of various cultures, communities, and identities—Lincoln Employees with Disabilities, Lincoln Employees' African American Network (LEAN), Out Professional Employee Network, Lincoln Laboratory New Employee Network, Recent College Graduates, Lincoln Laboratory Women's Network (LLWN), Lincoln Laboratory Hispanic and Latino Network (LLHLN), Pan Asian Laboratory Staff (PALS) network, and Lincoln Laboratory Veterans' Network (LLVETS).

Lincoln Laboratory is an active member of the National GEM Consortium, which, through partnerships with universities and industries, provides support to students from underrepresented minority groups who are seeking advanced degrees in science or engineering. The cornerstone of this effort is the internship program, which connects graduate students with employment opportunities at organizations engaged in technology development. In summer 2018, Lincoln Laboratory hired 19 GEM Fellows as interns; one of them is working at a field office in the Washington, DC, area. These interns have all been given letters of intent for post-graduation employment.

The following highlighted events from July 2017–June 2018 contributed to an inclusive environment.

In celebration of Hispanic Heritage Month, which runs from September 15 to October 15, LLHLN hosted a luncheon at the Minuteman Commons on Hanscom Air Force Base. Keynote speaker Hector Ruiz, former CEO of Advanced Micro Devices, spoke about his modest beginnings growing up in Piedras Negras, Mexico, where his parents instilled in him the importance of education. He explained that his upbringing led to his founding an initiative to connect 50% of the world to the internet by 2015 and his championing of the One Laptop Per Child initiative.

On November 8, 2017, Lincoln Laboratory held the seventh annual Veterans' Day Appreciation Luncheon. At the event organized by LLVETS, Admiral Steven Poulin, Commander of the First Coast Guard District, gave the keynote address, highlighting the contributions the 40,000-member US Coast Guard has made to national security.

The Lincoln Laboratory community celebrated the Lunar New Year on February 9, 2018—the year of the dog. PALS organized an event to showcase a variety of Asian cultures and cuisines. Performances by several local groups, including a Lion Dance ensemble and MIT's troupe of Bhangra (an Indian folk dance) dancers, rang in the New Year.

On February 27, 2018, more than 200 members of the laboratory attended the fifth annual LEAN Black History Month luncheon to celebrate the vision of Rev. Dr. Martin Luther King Jr. This year's keynote speaker was former NASA astronaut Joan Higginbotham, one of three black women to ever go to space and a person who embodies King's message to strive to reach "the mountaintop." Malik Oliver, a member of LEAN, noted that progress toward reaching the mountaintop "requires people to take action inside and outside of their communities, so we hope that people received that 'call to action' from the [MLK] celebration." LEAN also sponsored the second Black History Month documentary series in early February. Two documentaries, each followed by a discussion session, were shown. Ava DuVernay's Academy Award–nominated film *13th* begins with the economic history of slavery and post-Civil War racist legislation, and traces the evolution of US race relations to the 21st-century environment that led to the Black Lives Matter movement. The second film aired was *American Revolutionary: The Evolution of Grace Lee Boggs*, a biopic on 98-year-old Grace Lee Boggs, a Chinese American philosopher, writer, and activist in Detroit who has spent 75 years working in the labor, civil rights, and Black Power movements.

Lincoln Laboratory established and presented the first Cultural Awards. The LL Infinity Award recognizes an employee who has contributed to creating a welcoming, inclusive workplace, and the Leadership Award for Advancing Organizational Culture is presented to a member of management who has worked to foster an environment that respects all employees. These awards were given at the Cultivating Lincoln Achievement and Success Symposium sponsored by LLWN and held at the laboratory on April 13, 2018. The symposium addressed challenges and approaches to maximizing career growth and success. Regina Barzilay, Delta Electronics Professor at the MIT Computer Science and Artificial Intelligence Laboratory, and Erin Kelly, the Sloan Distinguished Professor of Work and Organizational Studies, spoke about their experiences forging careers in academia. Four breakout sessions addressed different avenues of career enhancement and methods of building leadership skills.

## Knowledge Exchange

### Technical Workshops

The dissemination of information to the government, academia, and industry is a principal activity of Lincoln Laboratory's technical mission. One way this goal is achieved is through annual workshops and seminars that bring together members of technical and defense communities. These multiday events foster a continuing dialogue that enhances technology development and provides direction for future research. The following workshops were held between July 1, 2017 and June 30, 2018:

- Advanced Prototype Engineering Technology Symposium
- Advanced Research Technology Symposium
- Advanced Technology for National Security Workshop
- Air, Missile, and Maritime Defense Technology Workshop
- Air Vehicle Survivability Workshop
- Anti-Access/Area Denial Systems and Technology Workshop
- Cyber Endeavour
- Cybersecurity, Exploitation, and Operations Workshop
- Defense Technology Seminar
- Homeland Protection Workshop Series
- Intelligence, Surveillance, and Reconnaissance Systems and Technology Workshop
- Lincoln Laboratory Communications Conference
- Software Engineering Symposium
- Space Control Conference

In addition, Lincoln Laboratory is a technical partner for the IEEE High Performance Extreme Computing Conference and the IEEE International Symposium on Technologies for Homeland Security.

## Publications

Knowledge dissemination is also achieved through the diverse venues in which Lincoln Laboratory researchers publish. Technical staff members publish articles in peer-reviewed journals and present at national technical conferences, such as the IEEE Radar Conference and the International Conference on Acoustics, Speech, and Signal Processing. Between July 1, 2017 and June 30, 2018, Lincoln Laboratory staff published 114 papers in proceedings from conferences, 53 articles in technical journals, seven self-published e-prints of technical articles, and 10 major technical reports available through the Defense Technical Information Center.

In a partnership with MIT Press, Lincoln Laboratory established a book series to present its fundamental research. Authored by Lincoln Laboratory experts, often with contributions from colleagues in academia and industry, the volumes in the MIT Lincoln Laboratory Series are intended as resources for researchers, engineers, and university educators and students. In June 2018, MIT Press published the sixth book in the series, *Mathematics of Big Data* by Jeremy Kepner and Hayden Jananthan. This college textbook presents the common mathematical foundations of big data analysis across a range of applications and technologies; each chapter ends with a selection of exercises for students.

## Research Collaborations

Technical staff at Lincoln Laboratory collaborate on projects with faculty and scientists at universities throughout the country; most collaborations are with researchers from MIT.

The Advanced Concepts Committee provides short-duration grants to MIT faculty and Lincoln Laboratory staff for focused research in basic and applied science and in technology areas of potential interest to the laboratory. These grants are awarded on a rolling basis throughout the year. In 2018, six collaborations were funded under the Advanced Concepts Committee and included ones on the electrically driven conversion of carbon dioxide to distillate fuels, germanium waveguides for security applications, thin film on-chip microbatteries, visually grounded speech translation without text, and the design of tunneling-based ultralow-power logic devices.

## Military Fellows Program

Lincoln Laboratory awards fellowships to support the educational pursuits of active-duty military officers who are fulfilling requirements for the US military's Senior Service Schools or for the Army's Training with Industry program, or who are working toward advanced degrees. This program helps the laboratory establish cooperative relationships with military officers and allows researchers to gain constructive insight from the frontline experiences of the officers who are assigned to technical programs within the laboratory. In AY2018, 45 military officers worked in various technical groups under fellowships. In summer 2018, 75 cadets and midshipmen from the US military academies participated in an internship program at the laboratory.

## Courses

Lincoln Laboratory hosts a number of multiday courses for user communities with which the laboratory interacts. These courses for invited military officers and DoD civilians enhance understanding of current research and the systems developed at the laboratory. In AY2018, the laboratory offered Introduction to Radar Systems; Networking and Communications; and a one-day course, ISR Systems and Technology.

In addition, through a program with the Naval War College in Newport, RI, technical staff present courses for naval officers; each term, courses are selected to address the college's needs. The courses scheduled in 2017 were in cybersecurity, ballistic missile defense, and space technology.

Lincoln Laboratory technical staff led activities offered during MIT's 2018 Independent Activity Period. During the semester intersession, Lincoln Laboratory staff members developed and led nine noncredit offerings: Build a Small Radar System; Free-Space Optical Communication; Hands-on Holography; Introduction to Autosec; Mathematics of Big Data and Machine Learning; RACECAR: Rapid Autonomous Complex-Environment Competing Ackermann-steering Robot; Software Radio; and Using Drones for Research: Data Processing and Legal Issues.

## Beaver Works

Beaver Works, a joint venture between Lincoln Laboratory and the MIT School of Engineering, facilitates project-based learning—a hallmark of an MIT education—and leverages the expertise and enthusiasm of MIT faculty, students, and researchers, and Lincoln Laboratory staff to broaden research and educational partnerships.

A key component of Beaver Works is the capstone project, which is typically associated with a two-semester design-and-build class that challenges students to develop an engineering solution to a real-world problem. This year, students in the MIT undergraduate courses 2.013 Engineering Systems Design and 2.014 Engineering Systems Development, offered by the Department of Mechanical Engineering in collaboration with Lincoln Laboratory, designed, built, and tested a self-powered, autonomous hull cleaning robot; developed ground penetrating radar; worked on laser-induced breakdown spectroscopy agriculture projects; designed an autonomous floating station-keeping platform; prototyped a hydrogen internal combustion engine; and continued the development of an aluminum-powered car. In conjunction with courses in the Department of Aeronautics and Astronautics, students advanced last year's project to build a large (24-foot wingspan) UAV that can sustain flight for five days without refueling; in summer 2018, the UAV is being flight-tested at a site on Cape Cod, MA.

## University Student Programs

Lincoln Laboratory offers a variety of research and internship opportunities to university students. Candidates in MIT's VI-A Master of Engineering Thesis program may spend two summers as paid laboratory interns, participating in projects related to their fields. Then, the students work as research assistants while developing their theses under the supervision of both Lincoln Laboratory engineers and MIT faculty. In AY2018, nine students chose to do their thesis research at Lincoln Laboratory. The laboratory also typically employs about a dozen other research assistants from across MIT's engineering departments.

Lincoln Laboratory collaborates with Worcester Polytechnic Institute (WPI) in its Major Qualifying Project (MQP) program, which requires a student to complete an undergraduate project equivalent to a senior thesis. Students participating in the program spend nine weeks during the fall term working on their projects full-time at Lincoln Laboratory. Their work at the laboratory culminates in a thesis-like document detailing their research and a presentation before WPI faculty and the laboratory community. In fall 2017, 10 students began their MQP research at Lincoln Laboratory.

Each summer, the laboratory hires undergraduate and graduate students from top universities as interns in technical groups. In addition to participating on technical projects, the students attend in-house demonstrations and seminars and give final presentations on their work to the laboratory community. In summer 2018, the laboratory hired 246 undergraduate and graduate students from 93 different colleges and universities to work as interns.

Throughout the year, cooperative-education (co-op) students from area colleges, such as Northeastern University and Wentworth Institute of Technology, work at the laboratory. This year, 95 co-op students from area schools were employed in technical divisions and service departments.

## Efficient Operations

Rapid increases in the complexity of today's business operations are compelling organizations to reassess their traditional practices and processes. Whether those organizations are commercial companies, academic institutions, government departments and agencies, or national laboratories like Lincoln Laboratory, they are confronted with challenges presented by the fast-paced expansion of technologies and applications used in business, and by stricter government regulations that lead to increased business auditing and reporting.

Organizations characteristically encounter a gap between the complexity of the evolving business environment and their capability to execute business efficiently. As complexity grows, organizations that do not revitalize their practices are left with a widening gap. Lincoln Laboratory is closing this gap. The Laboratory conducted an extensive efficiency study of operations and identified specific issues in staffing, training, business systems, and operating procedures that contribute to this capability gap. Subsequently, the laboratory has developed a strategic plan that is organized around three primary focuses to improve efficiency: the workforce, training, and business systems and processes.

### Workforce

As part of the strategic plan to improve business efficiency, Lincoln Laboratory created a professional career path for business managers, who partner with the leadership of the technical groups to satisfy requirements for financial reporting, to oversee the procurement of equipment and services to support technical programs, and to provide support to program managers, particularly in integrating work scope with schedule and budget resources (known as earned value management). Through a series of positions of increasing responsibility, the business manager track promotes the development of professionals who are highly skilled in the management of the financial and compliance requirements of R&D programs.

## Training

Lincoln Laboratory has always assured that its employees have access to training for complying with government regulations, safeguarding the laboratory's intellectual property, and protecting themselves from injury. The various types of training had been tracked by the departments or offices that had oversight of the requirements. They had used several systems that were not integrated, and enrollment in training sessions had been handled manually by multiple people.

To better track employees' completion of training, Lincoln Laboratory implemented a web-based application that enables employees to view their training requirements, complete online training, and enroll in classes. This application, called the Learning Center, is based on the SAP Learning Solution module but modified for the laboratory's particular needs. It provides a one-stop shop for the majority of internal training at the laboratory. The new system notifies departments, divisions, and groups of their employees' upcoming training expirations and provides reporting of employees' training completions. Training providers—such as the Security Services Department or the Environmental, Health, and Safety Office—identify employees' training requirements on the basis of attributes such as job category and work activity; administer their courses in the system's back-end interface; and use back-end reports to monitor compliance.

Through the Learning Center, the laboratory has decreased the effort and time spent by multiple people to track employees' training, has reduced the hours spent by trainers on delivering material that is now available online, and has empowered employees to manage their training needs.

## Digital Enterprise Transformation Project

The Digital Enterprise Transformation Project was initiated in 2017 to improve the services that enable and accelerate the laboratory's research. This enterprise-wide strategic initiative aims to increase efficiency and effectiveness, promote collaboration, and reduce operational risks.

The goal is to provide a trusted, robust, and integrated research business ecosystem that:

- Simplifies processes, applications, and technology
- Standardizes enterprise tools and processes
- Automates and digitizes to reduce manual processes and paper
- Provides intelligent data and access
- Delivers applications with intuitive design

This project comprises three phases: business process transformation, technology enablement, and simplification.

### Business Process Transformation

This first phase of the project is an assessment of the laboratory's current business processes and an analysis of industry best practices that could be adopted. The emphasis is on facilitating an "idea-to-R&D-product" strategy that integrates business operations with technical research activities and that implements procedures and tools to improve, simplify, and automate processes.

### Technology Enablement

The first initiative in the technology enablement component was the migration to SAP HANA. SAP HANA is a modern, in-memory, cloud-based, application-development platform designed to allow businesses to simplify information technology environments and business operations. The laboratory is using SAP HANA as its business applications digital core. Because SAP HANA removes the burden of maintaining separate legacy systems and siloed data, systems can run more efficiently in the digital economy. In a continuous cycle, Lincoln Laboratory's business processes will be reviewed, redesigned, and then implemented by SAP HANA, thereby improving organizational effectiveness by streamlining processes and enhancing capabilities.

### Simplification

During the simplification phase, enterprise-wide business capability enhancements defined and prioritized in the process transformation phase will be implemented on the laboratory's SAP HANA or cloud platforms. Implementation will be executed in waves as processes are streamlined and tools and applications are evaluated.

### Continual Improvement

An enduring outcome of the study is the newly formed Efficiency Improvement Team, co-chaired by the head of the Communication Systems Division and the head of the Security Services Department, and composed of representatives from across the laboratory. The team is overseeing the implementation of the study's recommendations. Efforts to address the identified action items have been initiated. The team is also executing a plan to continually review processes and strategize solutions to improve business capabilities.

## Community Outreach

### Education

Recognizing the importance of preparing young people for careers in science, technology, engineering, and mathematics (STEM), Lincoln Laboratory Community Outreach (LLCO) administers a significant program of STEM activities.

Science on Saturday, the laboratory's first STEM program, drew approximately 2,800 K–12 students, parents, and teachers to science demonstrations given by technical staff members during AY2018. Offerings for AY2018 included presentations on the science behind art, robotics, the redesignation of Pluto from a major to a dwarf planet, and the physics of color and sight. Student volunteers participated in several demonstrations.

The Lincoln Laboratory Radar Introduction for Student Engineers (LLRISE) summer program provides 18 high school students from across the country with a two-week, project-based course on radar fundamentals. The program includes instructional sessions on the basics of radar systems and radar imaging; workshops for building radar systems that can perform range-Doppler imaging; and opportunities to demonstrate the performance of the radars built during the workshops. The 2018 LLRISE began July 9. Two high school teachers, one from Puerto Rico and one from Stoneham, MA, participated in the program, evaluating the incorporation of this hands-on workshop into either their science curricula or an afterschool or summer enrichment program.

Beaver Works introduced the MIT Beaver Works Summer Institute (BWSI) in 2016. The 2016 summer STEM program taught 46 talented rising high school seniors how to program miniature racecars to autonomously navigate a complex racetrack. In 2017, BWSI added supplementary online lessons and new courses on autonomous air vehicles and cognitive assistants, and grew to 98 students. The 2018 program was expanded to eight courses, each with its online prerequisite tutorial, and 198 students who hail from 110 schools across the country. The new offerings are Build a CubeSat (a miniature satellite); Embedded Security and Hardware Hacking; Medlytics: Data Science for Health and Medicine; Hacking a 3D Printer; and Unmanned Air System–Synthetic Aperture Radar.

*At the music-themed Girls Who Build workshop, held at the Beaver Works facility in Cambridge, MA, on February 3, 2018, 30 volunteers from Lincoln Laboratory helped 40 high school students build speakers for a sound system and code software for manipulating music. The Girls Who Build series, begun in 2014, fosters interest in STEM through hands-on workshops that revolve around a different build project each year. The curricula for the Girls Who Build workshops are available through the MIT Open Courseware site.*

Three 2018 high school graduates interned at the laboratory as part of a program managed by the Boston-Lexington chapter of the Armed Forces Communications and Electronics Association International. The interns—Elena Parsons, Kelli Therrien, and Julia Maybury—were mentored by laboratory technical staff in the Chemical and Biological Defense, Advanced SATCOM Systems and Operations, and Bioengineering Systems and Technologies groups.

Other returning educational programs included Lincoln Laboratory Cipher, a weeklong course teaching cryptography to high school students; CyberPatriot, a national high school cyber-defense competition; and Robotics Outreach at Lincoln Laboratory, a program of robotics activities designed to prepare teams of K–12 students to compete in age-appropriate events sponsored by the For Inspiration and Recognition of Science and Technology organization.

## Community Service

The LLCO helps increase laboratory employees' awareness of events sponsored by charitable organizations. In 2017, the Lincoln Laboratory Ride to End Alzheimer's bicycling team and the laboratory's team in the Walk to End Alzheimer's together raised approximately $56,000 for research into the disease. Laboratory participants in the American Heart Association's Heart Walk raised $5,000 in 2017. Laboratory staff also walked and cycled for the CancerCare walk and the Pan-Mass Challenge.

The Lincoln Laboratory Hispanic/Latino Network raised almost $5,800 to support post-Hurricane Maria relief operations in Puerto Rico; in addition, the network collected toiletries, food, batteries, and water that were shipped to Puerto Rico through a ministry in Lawrence, MA. Support Our Troops, one of the LLCO's first community giving programs, is an ongoing campaign to collect and mail food, toiletries, and books to US soldiers overseas. In AY2018, Lincoln Laboratory sent 200 care packages to the troops. Participants in the Star-Spangled 5K Walk raised $2,145 to provide training for assistive dogs that work with wounded veterans.

Laboratory employees also donated hundreds of items to Toys for Tots, Cradles to Crayons drive for children's essentials, and a campaign to collect winter clothing for Puerto Ricans who relocated to the Boston area after losing their homes to Hurricane Maria.

## Summary

Lincoln Laboratory's portfolio of technology R&D programs continues to grow and is strategically balanced with programs that conduct large-scale system development, that perform rapid prototyping of new systems, that involve innovative, often multidisciplinary, research projects. Mission areas across the laboratory are pursuing answers to new challenges created by today's reliance on big data, cybersecurity, satellites, and electronic warfare.

The laboratory continues to transition its technologies to its government sponsors and to industry to help ensure that the US military has access to cutting-edge systems and that US industries remain international leaders in defense technology.

Ongoing improvements to administration and infrastructure, and a strong program in professional development, are all enabling the laboratory to achieve technical excellence in its work.

Community involvement is strong at the laboratory. Educational outreach programs are encouraging young people to consider careers as scientists and engineers. Many employees are engaged in activities, such as walks or volunteer programs, that support charitable causes.

In conclusion, Lincoln Laboratory is well prepared to achieve continued success in its mission of "technology in support of national security."

**Eric D. Evans**
**Director**