Aeronautics and Space Report of the President

Fiscal Year 2019 Activities

Aeronautics and Space Report
OF THE PRESIDENT

Fiscal Year 2019
Activities

The National Aeronautics and Space Act of 1958 directed the annual Aeronautics and Space Report to include a "comprehensive description of the programmed activities and the accomplishments of all agencies of the United States in the field of aeronautics and space activities during the preceding calendar year." In recent years, the reports have been prepared on a fiscal-year basis, consistent with the budgetary period now used in programs of the Federal Government. This year's report covers activities that took place from October 1, 2018, through September 30, 2019. Please note that these activities reflect the Federal policies of that time and do not include subsequent events or changes in policy.

On the title page, clockwise from the top left: **1.** During a spacewalk outside the International Space Station on August 22, 2019, astronaut Nick Hague and fellow crewmember Andrew Morgan install the second International Docking Adapter on the complex to enable commercial spacecraft from Boeing and SpaceX to carry astronauts to the station. Credit: NASA. **2.** Aircraft maintenance crews at NASA's Armstrong Flight Research Center prepare the remotely piloted Ikhana aircraft for a test flight. Credit: NASA/Ken Ulbrich. **3.** Artist's concept of the Suomi National Polar-orbiting Partnership (Suomi-NPP), an Earth-observing satellite operated by the National Oceanic and Atmospheric Administration (NOAA). Credit: NASA. **4.** Lidar data collected by NOAA aircraft showing Bixby Bridge and Bixby Creek along the coast of central California. Credit: NOAA. **5.** The 50-year anniversary of the Apollo 11 mission was celebrated on July 19, 2019, with full-motion projection-mapping artwork on the Washington Monument. Credit: NASA/Bill Ingalls. **6.** On May 29, 2019, NASA's Juno spacecraft captured this view of an area of Jupiter's clouds. Credit: Enhanced image by Kevin M. Gill based on images provided courtesy of NASA/Jet Propulsion Laboratory (JPL)–Caltech/ Southwest Research Institute (SwRI)/MSSS.

Table of Contents

The National Space Council

Since its revival by Executive Order on June 30, 2017, the National Space Council has advised and assisted the President on national space policy and strategy, advised on international space activities, and fostered closer coordination and cooperation among the domestic civil, national security, and commercial space sectors. The Council's Chair, Vice President Mike Pence, is supported by the National Space Council membership, which includes the heads of the agencies, offices, and departments responsible for the United States space enterprise.

At the President's direction, the Council meets regularly to publicly discuss the status of Administration priorities and propose new recommendations to the President regarding national space policy and strategy. In addition to an audience comprised of stakeholders from industry, government, academia, and non-governmental organizations, Council meetings are livestreamed to encourage public involvement and transparency.

The Council is supported by a Users' Advisory Group (UAG) comprised of non-federal senior leaders from industry, academia, and other non-governmental organizations. The UAG members are organized into six subcommittees: Exploration and Discovery, National Security Space, Economic Development and the Industrial Base, Technology and Innovation, Outreach and Education, and Space Policy and International Engagement. These subcommittees meet regularly to produce recommendations to the National Space Council for consideration.

Meetings of the National Space Council

The Council met on March 26, 2019, at the U.S. Space and Rocket Center in Huntsville, Alabama, marking the fifth meeting since the Council's revival in 2017. Prior to the meeting, the Vice President delivered remarks in which he issued the Administration's direction for a crewed mission to the lunar surface by 2024. The meeting included reports from the National Security Council, Department of Defense, Office of Science and Technology Policy, Department of Transportation, Department of Commerce, and the National Aeronautics and Space Administration (NASA). Subsequently, the Council heard two panels of expert testimony that focused on space exploration and human spaceflight. The Council voted unanimously to adopt recommendations to expedite a return to the lunar surface, as well as recommendations on space-related export controls.

On August 20, 2019, the Council convened for its sixth meeting at the Smithsonian National Air and Space Museum's Steven F. Udvar-Hazy Center in Chantilly, Virginia. This meeting focused on implementation of the Administration's direction for a crewed mission to the lunar surface by 2024 and sustained presence on the Moon as a proving ground for crewed missions to Mars. In particular, the meeting addressed measures necessary to reform the space sector, and highlighted innovative technologies that will expedite deep space exploration efforts. The Council voted on recommendations related to space nuclear power sources, exploration and international cooperation, commercial space and industrial base issues, and acquisition and workforce reform at NASA. At the recommendation of the National Space Council and the National Security Council, the President signed a new National Security Policy Memorandum to streamline the process of launching nuclear material for use in space exploration.

Space Policy Directive Implementation

Recommendations from previous meetings and other Administration priorities are articulated in Space Policy Directives, of which four have been issued since the Council's revival in 2017. The implementation of the existing SPDs is ongoing and summarized below.

Space Policy Directive-1 (SPD-1) amended the 2010 National Space Policy, also known as Presidential Policy Directive-4, to require NASA to return to sustainable human exploration of deep space with commercial and international partners. At the March 2019 meeting of the National Space Council, NASA announced it would expedite the return of the next American man and the landing of the first American woman on the Moon's lunar South Pole by 2024, followed by a sustainable lunar presence by 2028 in preparation for crewed missions to Mars. To accomplish the goals of SPD-1, the National Space Council has actively encouraged NASA to conduct necessary internal reforms. Negotiations and contracting processes are underway to include the unique capabilities of commercial and international partners in the effort.

Space Policy Directive-2 (SPD-2) requires certain departments and agencies to streamline regulatory requirements to ensure that there are no undue barriers to the acceleration of commercial space activities. Among them, the Department of Commerce is currently updating regulations on commercial remote sensing to keep United States industry at the forefront in an increasingly competitive global market. Not only are advanced remote sensing phenomena entering the market, but a wide range of data management and analytic tools are creating insights in a variety of market areas, including agriculture, finance, and insurance. The Department of Transportation is also working to streamline the Federal Aviation Administration's launch and reentry regulations to better reflect the increasing cadence and technological developments of the space transportation industry.

Space Policy Directive-3 (SPD-3) provided for the creation of the Nation's first space traffic management architecture to ensure protection of the national and economic security of the United States. The Departments of Defense and Commerce are developing transition plans and cooperative agreements to implement SPD-3. As final FY20 appropriations did not include adequate funding to do so, the FY21 President's Budget Request proposes the establishment of the Office of Space Commerce within the Office of the Secretary of Commerce and includes a $10 million request for this effort.

On February 19, 2019, the President held an Oval Office ceremony for Space Policy Directive-4 (SPD-4), which tasked the Department of Defense to create a legislative proposal to establish the United States Space Force. With the President's

signature on December 20, 2019, the Space Force was legally established as the sixth armed service within the FY2020 National Defense Authorization Act.

National Aeronautics and Space Administration

NASA

Human Exploration and Operations Mission Directorate

Exploration Systems Development

In 2019, the Exploration Systems Development (ESD) programs—Space Launch System (SLS), Orion, and Exploration Ground Systems (EGS)—continued to make steady progress toward the first missions of the Orion spacecraft and the SLS rocket that will lead the next steps of human exploration to the Moon and beyond, extending human exploration farther into space than ever before. Artemis 1 is planned to be the first integrated test of Orion, SLS, and the supporting ground systems launching from Kennedy Space Center (KSC) in Cape Canaveral, Florida.

Orion

Orion will serve as the exploration vehicle that will carry the crew to space, provide emergency abort capability, sustain the crew during space travel, and provide safe reentry from deep space return velocities. Orion will launch on NASA's new heavy-lift rocket, the SLS.

The Orion team made significant progress in fiscal year (FY) 2019. Orion's European Service Module (ESM), which will provide the power and propulsion for Orion during the mission, was completed and shipped to KSC in November 2018 for final assembly and integration. At KSC, the ESM completed final outfitting, integration, and testing. The team completed the building and outfitting of the

Orion Crew Module at KSC in June 2019. The Artemis Crew Module and ESM were mated to form the Artemis 1 Crew and Service Module (CSM). The CSM completed initial power-up, subsystem integration and testing, and final assembly in preparation for transport to NASA's Plum Brook Station in Sandusky, Ohio, for environmental testing under simulated extreme in-space conditions in the world's premier space environments test facility.

In July, the Orion team conducted a successful test of the Launch Abort System. From Cape Canaveral Air Force Station (CCAFS), a Northrop Grumman–provided booster lifted Orion to an altitude of 31,000 feet. The abort sequence was initiated at a point of maximum dynamic pressure, approximately 760 miles per hour (mph), when the abort motor fired, lifting the launch abort system and crew module to an altitude of 44,000 feet and carrying it away from the booster. The attitude control motor flipped the capsule end-over-end to properly orient it, and then the jettison motor fired, releasing the crew module for splashdown.

Both the Lockheed Martin and Airbus teams made significant progress on Orion's crew module in Florida and the ESM in Bremen, Germany. Assembly of the Artemis 2 spacecraft is well under way.

This year, NASA awarded the Orion Production and Operations contract to Lockheed Martin for a minimum of six Orion spacecraft. In parallel, the European Space Agency (ESA) approved funding for two more service modules. Work has begun on long-lead items with Artemis 3 crew module forgings arriving at machine shops in California and Illinois and service module primary structure assembly under way at Thales Alenia Space in Turin, Italy.

Space Launch System

The SLS is the most powerful and capable launch system in the history of spaceflight. NASA has developed and is actively refining a manufacturing capability to build, test, and fly an evolvable launch vehicle to support human and robotic exploration in the coming decades. The Block 1 SLS vehicle for the Artemis 1 flight is in final testing, and hardware is being shipped to KSC. Major assembly of the Artemis 1 core stage at Michoud Assembly Facility was completed, and all four RS-25 engines have been mated to the stage. In addition, the SLS team completed work on the Launch Vehicle Stage adapter and the left-hand booster aft skirt in

2019. The 10 booster motor segments for Artemis 1 are complete and will ship to KSC in 2020. At Marshall Space Flight Center (MSFC), teams have completed testing on three of four structural test articles in the largest campaign since the Space Shuttle.

The SLS government/industry team continued to make significant progress for missions beyond Artemis 1. The major structures for the Artemis 2 core stage have been welded, and the propellant tanks are in proof testing. The ten booster motor segments for Artemis 2 are complete, as are the four Artemis 2 RS-25 engines and RL10 engines for use in the upper stages of future Artemis missions. Production has started on the Interim Cryogenic Propulsion Stage (ICPS), Launch Vehicle Stage Adapter (LVSA), and Orion Stage Adapter (OSA) for Artemis 2.

This year, NASA tasked Boeing to begin procurement for additional core stages and a new Exploration Upper Stage. Boeing was also tasked with beginning production of the Artemis 3 core stage, which will send the first woman and the next man to the Moon.

Exploration Ground Systems

The Exploration Ground Systems (EGS) Program is responsible for overseeing ground systems upgrades and modifications to support the launch of the SLS and Orion spacecraft for the Artemis missions.

During 2019, EGS prepared for the launch and recovery of Orion on the SLS, as well as the support for other rockets that could potentially launch from KSC. The Artemis launch team completed several formal training simulations that will certify the team for the inaugural launch of the SLS rocket and Orion spacecraft. Teams have also been working to complete launch software while upgrades are finishing up in Firing Rooms 1 and 2.

Throughout the year, mechanics completed necessary engine maintenance on Crawler-Transporter 2, ensuring that it will be ready for Artemis 1. The crawlerway also went through conditioning, making sure the deep composition of river rock is stable enough to handle the incredible loads that include the mobile launcher, SLS, and Orion spacecraft. A variety of renovations at Launch Pad 39B were completed in August, including the final installation of support columns for the mobile launcher. Other additions include more than 90,000 new heat-resistant bricks on the walls of

the flame trench and the installation of a new flame deflector. EGS broke ground in December 2018 for a new liquid-hydrogen tank at the pad that will be the largest in the world. The storage facility will hold 1.25 million gallons of the propellant.

The mobile launcher rolled to Launch Pad 39B in June for final tests and checkouts throughout the summer and fall, including umbilical swing arm tests and a series of wet flow tests to verify the sound suppression system. Teams verified that systems on the launcher and the pad were working together appropriately. Just before the rollout, the engine service platform that will provide access to the core stage of the SLS was installed. EGS also conducted a Tail Service Mast Umbilical drop test inside the Vehicle Assembly Building to verify that the umbilicals will disconnect before launch. NASA selected Bechtel National, Inc., of Reston, Virginia, to design and build a second mobile launcher, known as Mobile Launcher 2 (ML2). Design is under way.

EGS participated with the Department of Defense in Underway Recovery Test-7 (URT-7) to practice recovering the Orion capsule once it returns from space. During URT-7, the recovery team embarked on the USS John P. Murtha, an amphibious U.S. Navy ship, in the Pacific Ocean. The main goal was to ensure that all of the new recovery equipment was validated and up to the task.

Commercial Crew Program

During FY 2019, NASA, Boeing, and SpaceX continued making technical and programmatic progress in maturing and certifying commercial crew transportation systems. This year, our commercial partners transitioned from final systems design and development efforts to flight hardware production, certification, and final acceptance testing as they prepared for and successfully conducted demonstration flights to the International Space Station (ISS). Boeing, SpaceX, and NASA continue to work issues identified during testing and flight as both commercial partners move closer to restoring America's human spaceflight capability.

Along with NASA, both partners are finalizing and approving Phase III hazard reports, conducting verification events, and closing out requirements verification closure products. Critical flight hardware and ground infrastructure are complete, including the manufacture of spacecraft, launch vehicles, and key ground systems.

Boeing completed several critical programmatic and technical milestones during FY 2019. Additionally, Boeing completed qualification testing of their Starliner spacecraft systems as well as launch vehicles and ground systems. They completed the manufacturing and acceptance testing of Spacecraft 3, Boeing's spacecraft to be used during the upcoming Orbital Test Flight (OFT), Boeing's uncrewed test flight to the ISS. Boeing's Spacecraft 1 and 2 are currently in final integration and testing in preparation for their upcoming Crewed Flight Test (CFT) and Post-Certification missions.

SpaceX completed several programmatic and technical milestones during FY 2019, including the Demo-1 Dragon Integration Checkpoint; the Certification Checkpoint; the Integrated System Review, Phase II, and Hazard Reports Checkpoint; Parachute Qualification, Part 1; the F9 Launch Vehicle Integration Review; and the Merlin Engine Qualification Checkpoint. In March 2019, SpaceX successfully completed its first of two ISS demonstration flights to the ISS. At 2:49 a.m. EST on March 2, SpaceX launched Crew Dragon's first demonstration mission from Launch Complex 39A (LC-39A) at NASA's KSC in Florida. This test flight without a crew on board the spacecraft demonstrated SpaceX's capabilities to safely and reliably fly astronauts to and from the ISS. The Crew Dragon accomplished the Nation's first autonomous docking with the ISS on March 3. NASA passed a major milestone on Friday, March 8, 2019, in its goal to restore America's human spaceflight capability when SpaceX's Crew Dragon returned to Earth after the five-day mission docked to the ISS.

Through the Commercial Crew Program (CCP), NASA is ensuring that the Agency's commercial partners' crew transportation systems are safe, reliable, and cost-effective. The certification process assesses progress throughout the production and testing of the partners' systems, which include launch vehicles, spacecraft, ground systems, and all aspects of operations.

Collaborations for Commercial Space Capabilities

The objective of the Collaborations for Commercial Space Capabilities (CCSC) is to advance private-sector entrepreneurial space activities. All CCSC partners continued to make technical and programmatic progress in maturing their respective commercial space capabilities.

International Space Station

In FY 2019, the ISS approached its 19th year of human habitation by astronauts from NASA and its international partners, enabling a continuous human presence living and working in space. The focus continues to be research and technology development in such disciplines as biology and biotechnology, Earth and space science, human research, and physical science. Research conducted on station in FY 2019 included experiments to better understand "normal" human adaptations to spaceflight, study how fluids shifts affect blood flow in astronauts, and learn how best to grow and harvest vegetables in preparation for long-duration missions. The ISS remains a testbed for technology, including tests of the Astrobee free-flying robot system, a new air quality monitor system for future Artemis Moon missions, the AstroRad Vest to protect astronauts from radiation caused by unpredictable solar particle events, and a new technology called tissue chips to advance human health research. Through the end of Expedition 58 (March 2019), the ISS had hosted over 2,775 investigations from more than 108 countries/areas. During that timeframe, the number of investigators with research on the ISS exceeded 4,000.

Enabling such research are frequent Commercial Resupply Services (CRS) flights from Northrop Grumman and SpaceX. Northrop Grumman completed two cargo flights and SpaceX completed three cargo flights to the ISS totaling more than 32,000 pounds of science investigations, spacewalking tools, and critical supplies delivered to the ISS. These cargo missions were complemented by those of our International Partners. Roscosmos provided three Progress cargo missions, and the Japan Aerospace Exploration Agency (JAXA) was responsible for the H-II Transfer Vehicle (HTV-8) mission during FY 2018. Additionally, more than 10,800 pounds of investigations and equipment were returned to researchers on Earth by the SpaceX Dragon capsule, while the Northrop Grumman Cygnus and HTV provided significant assistance, such as trash removal mechanisms, before they performed a destructive reentry. These resupply missions enabled ISS crewmembers to support more than 100 new U.S. science investigations to advance human space exploration to the Moon and Mars and conduct research sponsored by the U.S. National Laboratory to benefit life on Earth.

In addition to the CRS missions, there were four successful Soyuz crew missions, one Soyuz test mission, an aborted crew mission, and two Soyuz crew return missions occurring in FY 2019. The departure of Soyuz 55S in December 2018 denoted the end of Expedition 57, which was supported by only three ISS crewmembers. This was due to the Soyuz 56S mission in October 2018, carrying a pair of astronauts, being cut short by a technical problem that triggered an ascent abort minutes after launch and a safe landing back on Earth. The ISS was crewed by only three astronauts during Expedition 58, as well as by the crew arriving on Soyuz 57S just prior to the Soyuz 55S departure. The launch of Soyuz 58S in March 2019 returned the ISS to its typical six-person crew and marked the beginning of Expedition 59. Onboard Soyuz 58S were the two astronauts (NASA's Nick Hague and Roscosmos's Alexey Ovchinin) whose 56S mission did not reach orbit earlier in the year, as well as rookie NASA astronaut Christina Koch. Astronauts Koch and Hague are participating in extended-duration missions of 11 months and 10 months, respectively, to provide researchers with the opportunity to observe the effects of long-duration spaceflight to prepare for human missions to the Moon and Mars. On December 28, 2019, Koch set a record for the longest single spaceflight by a woman, eclipsing the previous mark of 288 days set by Peggy Whitson. The departure of Soyuz 57S in June 2019 and the arrival of Soyuz 59S in June and July, respectively, marked the transition from Expedition 59 to Expedition 60, which concluded in early October 2019. Additionally, Roscosmos performed a test flight on the Soyuz 60S mission, which carried no crewmembers but tested vehicle modifications for integration with the Soyuz 2.1a launch vehicle. It was the first-ever unpiloted Soyuz mission to the ISS.

Four U.S. extravehicular activities (EVAs), in addition to two Russian Segment EVAs, were conducted during FY 2019. A pair of spacewalks in March 2019 completed two sets of battery replacements and power upgrades on the orbital laboratory. Nickel-hydrogen batteries were replaced with newer, more powerful lithium-ion batteries on two separate power channels. The batteries store power generated by the station's solar arrays to provide power to the microgravity laboratory when the Station is not in sunlight as it circles Earth during the orbital night. The spacewalking work performed continues the overall upgrade of the station's power system that began with similar battery replacement during spacewalks in

FY 2017. A spacewalk in April 2019 successfully established a redundant path of power to the Canadian-built robotic arm, known as Canadarm2, and installed cables to provide for more expansive wireless communications coverage outside the orbital complex, as well as for enhanced hardwired computer network capability. On the 218th spacewalk in support of station assembly, maintenance, and upgrades, the EVA crew successfully installed the second of two international docking adapters (IDAs). The IDAs, or commercial docking ports, will be used for the future arrivals of Boeing CST-100 Starliner and SpaceX Crew Dragon commercial crew spacecraft. NASA's commercial crew partnership with Boeing and SpaceX will restore launches of astronauts from American soil on American rockets and maximize the time U.S. crews can dedicate to scientific research and technological advances aboard the orbiting laboratory. Regular human space transportation to the space station is a critical step to opening the space station for commercial business to enable the growth of the U.S. commercial space sector and the development of a robust low-Earth orbit (LEO) economy. NASA astronauts assigned to the first CCP flights have trained extensively with operational teams covering all phases of flight in preparation for the flight tests with crewmembers planned for 2020.

In June 2019, NASA announced a five-point plan to open the space station for business so that U.S. industry's innovation and ingenuity can accelerate a thriving commercial economy in low-Earth orbit. Prior to the announcement, more than 50 companies were already conducting commercial research and development on the space station via the ISS U.S. National Laboratory. NASA's plan enables the use of Government resources for commercial activities, creates the opportunity for private astronaut missions to the space station, enables commercial destinations in low-Earth orbit, identifies and pursues activities that foster new and emerging markets, and quantifies NASA's long-term demand for activities in low-Earth orbit.

Space Life and Physical Sciences Research and Applications (SLPSRA)

Human Research Program (HRP)

In 2019, NASA sponsored research to mitigate human health and performance risks associated with long-duration spaceflight. NASA ISS crewmembers

conducted 15 biomedical investigations during each of the ISS mission increments, completed five major ISS flight investigations, and initiated six new flight investigations with the start of pre-flight baseline data collection or in-flight ISS data collection. ISS studies to mitigate the risk of long-duration spaceflight included the following: 1) standardized behavioral measures for detecting behavioral health risks during exploration missions; 2) assessed exploration food technology on how a repetitive menu affects food acceptability and implemented a study to assess long-term food stowage to preserve quality during spaceflight; 3) executed ISS Spaceflight Standard Measures project that collects a set of core measurements from astronauts to better define human spaceflight risks before, during, and after long-duration missions; 4) assessed human factors and performance on the impacts of switching operational tasks within a crew in order to reduce negative consequences and improve individual and team effectiveness; 5) conducted research supporting the development of a continuous fresh-food production system; and 6) undertook physiological research using quantitative computerized tomography (CT)– and Magnetic Resonance Imaging (MRI)–based modeling assessments of dynamic vertebral strength and injury risk following ISS long-duration spaceflight.

ISS research publications for both the One-Year Mission and Twins Study were released in *Aerospace Medicine and Human Performance and Science*, respectively. These publications documented the health impacts of long-duration spaceflight from physiological to genomic levels. Initial assessments identified spaceflight-specific changes including decreased body mass, telomere elongation, carotid artery distension and increased intima-media thickness, altered ocular structure, transcriptional and metabolic changes, DNA methylation changes in immune- and oxidative-stress related pathways, gastrointestinal microbiota alterations, and cognitive changes post-flight. Although average telomere length, global gene expression, and microbiome changes returned to nearly preflight levels within six months after return to Earth, increased numbers of short telomeres were still observed, and the expression of some genes was still altered. These multi-omic, molecular, physiological, and behavioral datasets provide a valuable roadmap of the putative health risks for future human spaceflight.

HRP supported the Translational Research Institute for Space Health (TRISH) and its mission to lead a national effort to translate cutting-edge emerging research

into mitigation strategies for exploration missions, as well as to educate the next generation of space biomedical scientists. TRISH focuses on rapidly translating fundamental research concepts into practice, thereby generating tangible health outcomes to protect astronaut health. During 2019, TRISH had 56 active projects in its science and technology pipeline and released two research announcements: 1) Biomedical Research Advances for Space Health and 2) an industry solicitation asking for proposals from small U.S.-based companies for technologies that would be essential for self-reliant healthcare in deep space. TRISH also solicited and funded outstanding postdoctoral fellows and supported training for future NASA flight surgeons.

In 2019, HRP completed the following key milestones:

- Delivered the Advanced Twin Lifting and Aerobic System (ATLAS) deep space exercise system to the NASA Crew Health and Performance Systems Capability Leadership Team (SCLT) for testing and evaluation. ATLAS is an advanced servomotor-based exercise device for resistance and aerobic training, designed to support long-duration space missions where mass and volume are severely limited. ATLAS evaluation is ongoing, with a potential ISS demonstration and testing planned for next year.
- Implemented a 60-day bedrest study with the European Space Agency (ESA) and German Aerospace Center (DLR) to evaluate centrifugation (artificial gravity) as a countermeasure for physiological changes induced by spaceflight to protect crew health during future space exploration missions. HRP completed the first campaign of the Artificial Gravity Bed Rest-ESA (AGBRESA) study at the DLR envihab facility and initiated the second campaign, each with 12 research subjects. To assess artificial gravity effectiveness, the study uses three test groups: control not using the centrifuge, centrifuge for 30 minutes per day without stopping, and centrifuge intermittently for a total of 30 minutes.
- Completed two HRP studies in collaboration with the National Science Foundation (NSF) during the 2019 winter-over period at the NSF's McMurdo and Amundsen-Scott (South Pole) stations. The studies involved 24 winter-over research subjects and assessed the effects of a remote location, extreme isolation, and confinement on team dynamics.

The Shared Cognitive Architectures for Long-term Exploration (SCALE) study examined the changes in and effects of shared mental models within teams in long-duration isolated and confined environments, and the Crew Recommender for Effective Work in Space (CREWS) study collected data on team composition and impacts to performance to assist in team composition decisions for future missions.

- Executed long-duration isolation and confinement studies at the Nezemnyy Eksperimental'nyy Kompleks (NEK) facility in Moscow, Russia, in collaboration with the Russian Institute for Biomedical Problems. In the SIRIUS-19 120-day mission, crewmembers conducted experiments on behalf of nearly 80 different researchers from around the world, including seven studies funded by HRP. The HRP studies focused on behavioral health and performance measures on topics such as team interactions, task switching and entrainment, biomarkers related to stress, crew autonomy, and multicultural factors in team dynamics.

Biological and Physical Sciences (BPS)

Under the management of the SLPSRA Division, BPS at NASA continues its strategy to explicitly align research on two primary thrusts, Enabling Exploration and Pioneering Scientific Discovery. This structure is in keeping with the framework for research prioritization recommended by the National Research Council in its Decadal Survey for Life and Physical Sciences at NASA and reaffirmed in its mid-term assessment report released in 2018.

In 2019, SLPSRA directly contributed to the National Quantum Initiative Act goals of 2018 through activities in several important areas: SLPSRA's quantum sensor-based Cold Atom Laboratory (CAL) performed research directed by a Principal Investigator (PI) cadre that includes three Nobel Laureates. CAL generates a quantum state of matter known as the Bose-Einstein Condensate under conditions on the ISS that are not available to ground-based investigations. In FY 2019, CAL produced results that these investigators are now readying for publication. This research demonstrated the ability of the United States to deploy and operate quantum sensor technology in space, putting the United States at the forefront of scientific and commercial development of quantum sensor technology

for space applications. To build and expand on CAL's foundation, in 2019, SLPSRA selected two science definition teams and tasked them with identifying future research directions in important quantum technology areas, with the goal of developing the technology necessary to facilitate the maturing of quantum technologies for both basic science investigations and national security and space-based commercial applications. One team began defining the work required for a deep space quantum link, which is an optically based quantum communication technology that will allow researchers to perform unprecedented tests of the nature of reality using quantum entangled particles over light-second distances from the Moon. An investment in such a quantum link has wide applications in quantum communications, quantum networks, and cryptographic applications such as quantum key distribution.

Performing electromagnetic levitation in the microgravity environment of the ISS provides an opportunity for a better understanding of the physical properties of metals and bulk metallic glasses. Levitation provides the opportunity to perform "containerless" experiments that eliminate the interactions between a sample and the container wall. The microgravity environment removes the effects of gravity as the samples are melted and solidified. Levitation experiments in FY 2019 provided data for several PIs. Objectives of these PIs included 1) manufacturing better cast superalloy components to improve the efficiency, safety, and reliability of rocket and jet engines; 2) understanding the ability of metallic liquids to form bulk metallic glasses, which are an emerging class of materials with several applications, including cryogenic gears for planetary exploration; and 3) investigating the thermophysical properties of high-temperature materials to allow more efficient and reliable production of metallic parts using these alloys.

NASA conducted several experiments in two campaigns on the ISS that provided data on cement solidification both in the microgravity environment and in a simulated ⅙ gravity environment that mimics lunar gravity. These experiments provided investigators with the opportunity to fully explore the complex process of cement solidification because we do not fully understand how this process will work in an altered gravity environment. While investigators are still analyzing and quantifying the data, microstructure images show vast differences in morphology between cement cured in Earth gravity and cement cured in reduced gravity.

That is because microstructural development of hydrating cement occurs in stages during both the hydration reaction and the hardening process. Minimizing gravity-driven phenomena, such as thermosolutal convective flow and sedimentation, ensures crystal growth strictly by diffusion, which produces a microstructure in altered gravity that is different than that observed in typical laboratory conditions on Earth. Investigators expect different microstructures and, consequently, altered material properties between cements solidified on Earth and in reduced gravity. Understanding the results of these experiments will allow NASA to be able to predict cement performance in an altered gravity environment in order to successfully use in situ resources to construct durable planetary habitats. This type of construction could eventually reduce the amount of resources NASA needs to launch, thus reducing the overall costs.

Experiments with small particles suspended in a fluid, known as colloids, developed and validated a procedure to customize average particle separation in the colloid by varying the temperature of the sample cell. The goal of this experiment was to increase the number of charge carriers in a gel colloidal system and hold open the possibility for a significant increase in solar panel efficiency.

ISS experiments demonstrated that flames could be stabilized using electric fields under conditions that would not otherwise support combustion. Because industrial burners can be modeled as a collection of non-buoyant flamelets, these results could lead to new, ultra-lean combustor designs featuring much cleaner-burning flames.

SLPSRA-funded investigators began a new series of combustion experiments in NASA Glenn Research Center's (GRC) Zero-Gravity drop tower facility in FY 2019. The high-pressure transcritical combustion (HPTC) experiments investigated the spontaneous ignition of a fuel droplet injected into a high-pressure, high-temperature environment. These experiments are a simplification of the processes occurring in practical engines and leverage discoveries in previous ISS experiments. The research will provide needed insights into the high-pressure ignition and combustion processes that are critical to the design of future engines that will operate at much higher pressures than current engines. The experiments showed unique and two-stage ignition behavior not previously reported in the literature.

In 2019, NASA made significant progress to enable exploration in the area of space biology. Two flights of the Veggie-04 experiment, a joint Space Biology and HRP experiment, were conducted in order to help investigate food production systems for the space station and long-duration exploration missions and to test specific pick-and-eat crops for micronutrient delivery and consumption using foods like mizuna. This study is exploring the viability of growing fresh food in space to support astronauts on long-term missions. The salad-type plants are harvested after 28 days of growth, with some samples stowed for analysis and the rest taste-tested by the crew aboard the station. This spaceflight experiment will contribute to NASA's efforts to develop reliable autonomous culture of plants that assist life-support functions for long-duration missions.

In 2019, the first-ever comprehensive characterization of the microbiology of the ISS was completed and published. Over several years, numerous surfaces of the ISS were repeatedly sampled. It was discovered that different surfaces and ISS locations had unique and shared microorganisms, composed of benign and potentially pathogenic microorganisms. Also, strains of bacteria, which were previously unidentified on Earth, were discovered. The investigators determined that the ISS microbial flora fluctuated over time, depending on the crew and cargo exchanges. This study advances knowledge of microbial communities of a built, closed system environment and how this environment interacts with the astronauts. The findings from these studies will aid in evaluating and refining risks to crew health for long-duration deep space missions and in developing crew vehicles and human habitats for the Moon and Mars sustained missions or in better understanding closed and semi-closed environments on Earth to further assess human risks.

In 2019, through rodent tissue-sharing experiments, Space Biology investigators discovered that spaceflight-based changes in the gut bacterial flora (microbiota) of mice may be attributed to specific space environmental factors. This study demonstrated how spaceflight-caused changes in the gut microbiome are integrated with the functions of other tissues, as observed on Earth. The findings may provide directions for developing nutrition- and probiotic-based countermeasures for maintaining crew health during long-duration space missions in low-Earth orbit and lunar expeditions. Studies of this type could pave the way for developing methods

for maintaining health using "simple" solutions that are usable by space tourists and commercial ventures.

Sample analysis for the Rodent Research (RR)–9 joint experiment was completed in 2019. One Space Biology investigator characterized the effects of the spaceflight environment on eye physiology and function. The investigator discovered that this environment caused damage to the retina and the blood-retinal barrier. This study provided scientific data that characterized a new risk factor for human spaceflight. The findings confirmed the need for countermeasure development to protect the eye and blood-retinal barrier to maintain ocular health during long-term human spaceflight. Another investigator from the RR-9 experiment characterized the effects of the spaceflight environment on knee joint function and physiology. In 2019, the investigator discovered that the cartilage of the knee joints in mice was completely lost due to exposure to the microgravity environment, resulting in bone-to-bone contact at these joints. The findings from this study add a new risk factor for human exposure to microgravity, which could affect physical activity in microgravity and upon return to gravity (on Earth, the Moon, or Mars) and indicates the need for new countermeasure development to protect cartilage. The RR-12 experiment was also executed on orbit in 2019. The RR-12 mission will investigate the effects of spaceflight on both the primary immune response and secondary immune response. When the immune system of an individual animal encounters a particular toxin or pathogen for the first time, it triggers the primary immune response, activating the production of early antibodies and memory cells that later "remember" the toxin or pathogen. Subsequent encounters with the same toxin or pathogen trigger the secondary immune response. The mission could uncover new ways to improve vaccines and therapies for humans both in space and on Earth.

In 2019, Space Biology investigators developed a partial weight-bearing method for rats and demonstrated that the method has no impact to rodent stress or overall well-being. This method enables studying partial gravity (e.g., Moon and Mars gravity) in a ground laboratory to test basic hypotheses, conduct studies for proof of concept, and define science requirements for ISS experiments. The partial weight-bearing method has resulted in the identification of a nutraceutical resveratrol, which is an over the counter anti-oxidant found in berries and peanuts

that prevents muscle deconditioning. This is an important system that can be used to test countermeasures for use in deep space exploration missions to the Moon and Mars.

The Micro-15 experiment, launched on SpaceX CRS-18 in July 2019, investigated the fundamental biology of mammalian stem cells during differentiation into mouse embryos. Results from this study will be used to advance the understanding of stem cell differentiation processes and mechanisms for normal embryo development and tissue regenerative processes and to characterize the impacts of the spaceflight environment on stem cell differentiation. This has far-reaching implications for risks related to tissue degeneration and supports countermeasure identification related to maintenance or induction of tissue regeneration and wound healing on Earth and in space.

The Spectrum Multi-Fluorescence Spectral Imager (Spectrum) was delivered to the ISS on the NG-12 mission in November 2019. Spectrum will provide a new, valuable capability for Space Biology researchers to study the effects of microgravity on plants and other organisms. Using Spectrum, scientists can identify which genes are expressed in biological cells through fluorescent imaging. Understanding which genes are expressed in biological cells is key to understanding how biological organisms respond and adapt to the stresses of spaceflight. This knowledge will help future space researchers select or genetically engineer plants for survival in space—a critical component for food production during long-duration space missions or settlements on the Moon or Mars.

The Passive Orbital Nutrient Delivery System (PONDS), developed in 2019, is a new plant-growth approach that contains both an area for a contained plant-growth substrate and a reservoir for water and/or plant nutrient solutions. The system provides more reliable water delivery to seeds for germination while avoiding overwatering. PONDS units can be easily and cheaply fabricated for use in classrooms in an effort to inspire the next generation of students to pursue science activities, as well as in home gardens. This project was featured in *Popular Science: https://www.popsci.com/iss-ponds-space-plants/.*

In February 2019, Space Biology selected four studies to reach new heights as it sends science experiments to the Moon and back to Earth as part of the Artemis 1 mission to the Moon. Plant seeds, yeast, algae, and fungi will travel in the Artemis

crew capsule to investigate how the deep space environment, especially radiation, affects these specimens. These studies are key pathfinder investigations that will provide the first data on how the cislunar environment impacts biology since Apollo 17 occurred 47 years ago. The investigations will use cutting-edge, state-of-the art science techniques not available in 1972 to provide unprecedented data to characterize the physiology, genetics, and mechanism of life in deep space. The findings will be used to define future experiments with the objectives of fostering human exploration to the Moon and Mars.

The NASA GeneLab open science database (*https://genelab.nasa.gov*) has been increasingly successful in enabling scientific discovery and space exploration through multi-omics data mining of its 221 spaceflight datasets. By the end of 2019, GeneLab had been the sole source for 12 scientific peer-reviewed articles, reflecting the generation of new knowledge on how life adapts to space through the aggregate analysis of multiple spaceflight omics datasets (e.g., changes in DNA content, gene expression, or protein levels) archived in GeneLab. Many of these publications were the result of collaborative analysis done by more than 120 users from around the world, who joined the GeneLab Analysis Working groups and volunteer their expertise in bioinformatics to extract more information from these previously published data. These findings advance our understanding of key crew-health threats for long-duration exploration and demonstrate the power of open science.

Human Spaceflight Capabilities

During FY 2019, Rocket Propulsion Testing (RPT) safely performed 884 tests of rocket engines and components at various levels of thrust. Hot fire test time totaled 36,643 seconds. In addition to the hot fire tests, RPT facilities performed 603 hours of thermal vacuum testing for vehicle certifications and facility checkouts in preparation for the vehicle certifications. These tests were completed with only three facility-caused test delays, resulting in a 99.7 percent test stand availability, exceeding the Agency performance goal of 90 percent as defined in the NASA Management and Performance report.

RPT performed seven RS-25 engine tests on the SSCusaf A-1 test stand. The tests accounted for 3,197 seconds of hot fire test time in a multi-year effort

to certify the engine for use on the SLS core booster stage. Other test activities included testing support for SpaceX, Aerojet Rocketdyne, other NASA programs, and Department of Defense (DOD) projects such as the U.S. Air Force (USAF)–designed and –developed Hydrocarbon Boost components. The Hydrocarbon Boost Program is a critical effort to support the DOD objective of replacing the RD-180 engine used in the Atlas V launch vehicle. In addition to supporting the USAF hydrocarbon program, NASA continued performing Aerojet Rocketdyne hydrocarbon full-scale component testing on E-1 Test Stand, Cell 1, for the AR-1 engine program.

At the Johnson Space Center (JSC) White Sands Test Facility (WSTF), engineers conducted tests to support NASA's Orion and CCP, Aerojet Rocketdyne, the Missile Defense Agency, and the USAF Peacekeeper missile-safing project, as well as hot fire testing for the USAF Minuteman missile life-extension program. On Test Stands 301, 301A, 401, and 406, RPT continued testing the Orion service module (provided by ESA), the Boeing CST-100 service module, the launch abort engines, the reaction control system, and the orbital maneuvering and attitude-control thrusters.

At GRC's Plum Brook Station (PBS), the In Space Propulsion (ISP) facility performed Evolvable Cryogenics Project (eCRYO) and Structural Heat Intercept, Insulation and Vibration Evaluation Rig (SHIIVER) in a simulated space environment (vacuum and thermal). The ISP facility also supported the Science Mission Directorate (SMD) Balloon Program. RPT also continued collaborating with GRC to refurbish the ISP facility to perform propulsion-related testing for systems of up to 30 kilopounds-force with 300 seconds of run time.

At MSFC, RPT continued testing rocket engine components manufactured using select laser melting and other additive manufacturing processes, furthering the capabilities of both NASA and RPT.

The RPT Program Office pursued results from the RPT Benchmarking Initiative for Test Efficiencies and Affordability performed in FY 2018. The goal is to identify tangible changes that could be implemented at the participating RPT in order to improve RPT operational efficiencies and decrease costs. Results of the benchmarking initiative will be used to ensure that efficient and affordable RPT test services are available to current and future test customers.

Launch Services

The Launch Services Program (LSP) provided expertise and active launch mission management for over 60 NASA scientific spacecraft missions in various stages of development. LSP continuously works with the U.S. commercial launch industry, assessing their designs and providing advice in an effort to expand the selection of domestic launch vehicles available to NASA's missions, thereby nurturing a competitive commercial launch service environment.

In FY 2019, LSP acquired new launch services for three NASA missions through competitively awarded launch service task orders for the Science Mission Directorate: The Imaging X-Ray Polarimetry Explorer (IXPE) will launch aboard a Falcon 9 Full Thrust in April 2021; the Double Asteroid Redirection Test (DART) will launch aboard a Falcon 9 Full Thrust in July 2021; and the Lucy mission will launch aboard an Atlas V in October 2021. Both IXPE and Lucy are planned for launch from the East Coast's CCAFS in Florida, with DART launching from the West Coast at Vandenberg Air Force Base in California. Currently, launch services task order acquisitions are in work for three science missions: the Geostationary Operational Environmental Satellite–T (GOES-T); the Psyche mission (with the Escape and Plasma Acceleration and Dynamics Explorers [EscaPADE] and Janus missions as secondaries); and the Plankton, Aerosol, Clouds, and ocean Ecosystem (PACE) mission. In addition, NASA and LSP continue to partner with several universities and NASA Centers to launch small research satellites through the CubeSat Launch Initiative (CSLI), providing rideshare opportunities for small-satellite payloads to fly on upcoming launches when space is available. These partnerships have provided regular educational opportunities for students in science, technology, engineering, and mathematics (STEM) disciplines, thereby strengthening the Nation's future workforce. As of FY 2019, CubeSats had been selected from 39 states and Puerto Rico, with 101 missions launched and 35 manifested on NASA, National Reconnaissance Office, USAF, and commercial missions. In FY 2019, 19 CSLI CubeSat missions were launched. The Venture Class Launch Services (VCLS) contracts were established to foster a commercial launch market dedicated to flying small-satellite payloads. VCLS serves as an alternative to the current rideshare approach, in which one or more CubeSats or other small

payloads take advantage of excess payload capacity on a rocket whose primary mission is to launch a larger satellite. The VCLS rockets also serve as a cost-effective launch option for small-satellite primary missions with a higher risk tolerance. In December 2018, Rocket Lab USA successfully launched 10 NASA CubeSats to low-Earth orbit aboard the Electron launch vehicle on the first-ever VCLS mission. Virgin Orbit (formerly Virgin Galactic) will follow with a scheduled launch in the first half of 2020 aboard the LauncherOne launch vehicle. The LSP also successfully completed Category 3 certification of the SpaceX Falcon 9 Full Thrust launch vehicle and continued pre-certification activities with Blue Origin's New Glenn, United Launch Services' Vulcan, Northrop Grumman's Omega, and SpaceX's Falcon Heavy launch vehicles. The LSP will continue to work toward certifying new commercial launch vehicles to launch high-value payloads.

Along with full end-to-end launch service management, the program continues to offer advisory support, expertise, and knowledge to NASA programs and projects utilizing launch services not procured and managed by LSP. The program is currently providing these advisory services to several programs and missions, including ISS Cargo Resupply Service missions; Gateway; the CCP; SMD's James Webb Space Telescope (JWST), and the NASA–Indian Space Research Organization Synthetic Aperture Radar (NISAR) mission.

Advanced Exploration Systems (AES)

The Advanced Exploration Systems Division manages the Gateway program, the Human Landing System (HLS) program, Artemis surface suit development, and risk-reduction technologies for lunar and Mars exploration. AES infuses technologies and develops high-priority capabilities using a combination of unique in-house activities and public-private partnerships to develop and test prototype systems that will form the basis for future human spaceflight missions.

Risk-Reduction Technologies

AES develops and demonstrates prototype exploration systems to reduce mission risk, validate operational concepts, leverage partner capabilities, and lower life-cycle costs to help enable lunar and deep space missions. In FY 2019, AES

continued to advance technologies related to deep space habitats following the successful completion of ground-based prototype testing, identified and addressed knowledge gaps for lunar environments and resources, and leveraged the ISS as a testbed to advance the technology readiness of deep space systems. AES accomplished the following risk-reduction milestones in FY 2019:

- Launched the Spacecraft Atmosphere Monitor (SAM) to the ISS. A compact, autonomous, real-time air-quality monitoring system, SAM immediately detects trace contaminants that pose potential threats to crewmembers' well-being. This advancement is critical for future human spaceflight missions, especially missions to the Moon and Mars, when sample return to Earth will not be an option.
- Delivered the Universal Waste Management System (UWMS) for Orion. The UWMS is the next-generation space toilet that has been redesigned for greater crew comfort, more efficient water recovery, and less complex systems that reduce volume and maintenance. A duplicate UWMS will be installed on the ISS next year, and it is also compatible with Gateway standards.
- Completed a successful Ascent Abort-2 flight test for Orion. Orion's Launch Abort System (LAS) is an integral part of ensuring crew safety during launch. This state-of-the-art crew escape system is attached to the top of the spacecraft, ready to propel the crew module away from the SLS rocket within milliseconds should a life-threatening event arise during launch.
- Completed ground testing of five NextSTEP-2 prototype habitats from Bigelow Aerospace, Boeing, Lockheed Martin, Northrop Grumman, and Sierra Nevada Corporation. AES evaluated the different full-scale, deep space habitat ground prototypes to identify the capabilities, habitat layouts, and design features that would be most enhancing to deep space missions and crew performance. Astronaut test subjects conducted the same representative multi-day mission simulations in each of the contractor's prototypes.
- Conducted proof-of-concept testing of active radiation shielding using electric dipoles. AES conducted proof-of-concept testing of active radiation shielding at the Brookhaven National Laboratory. The experiment

used high-voltage electric fields to deflect incoming charged particles, showing that it may be a feasible method to protect astronauts from the harmful effects of deep space radiation on long missions. Active radiation shielding could be much lighter weight than passive radiation shielding that is integrated with spacecraft structures.

- Demonstrated Refabricator operations on the ISS (integrated 3D printer and recycler). The first integrated recycler and 3D printer was successfully installed onboard the ISS. The Refabricator turns plastic materials of various sizes and shapes into feedstock used to 3D print items. The entire process happens in a single automated machine about the size of a mini refrigerator.
- Launched three Astrobee free flyers to the ISS. The free-flying Astrobee robotic system will help astronauts reduce time they spend on routine duties, leaving them able to focus more on the things that only humans can do. Working autonomously or via remote control by astronauts, flight controllers, or researchers on the ground, the robots are designed to complete tasks such as taking inventory, documenting experiments conducted by astronauts with their built-in cameras, or working together to move cargo throughout the station. In addition, the system serves as a research platform that can be outfitted and programmed to carry out experiments in microgravity.

Gateway

Following Vice President Michael Pence's announcement on March 26, 2019, that NASA would return to the Moon earlier than the original 2028 goal, the Gateway team refocused the assembly plans into two phases. Phase 1 focused on a minimal configuration that can be deployed quickly and provide significant infrastructural support to the 2024 landing mission, and Phase 2 focused on long-duration surface stays and international partnerships. Since then, the team has

- awarded a contract to Maxar Technologies to develop and demonstrate power, propulsion, and communications capabilities for the Power and Propulsion Element (PPE), the first Gateway component to launch to lunar orbit;

- issued a draft request for proposals (RFP) for Gateway logistics services, followed quickly by a final RFP; and
- issued an RFP to Northrop Grumman to develop the minimum-capability Gateway habitation module, known as the Habitation and Logistics Outpost (HALO).

Human Landing System

The Human Landing System team conducted the second Design Analysis Cycle (DAC) meeting from March 25 to 27, watching together as Vice President Pence addressed NASA and the Nation on March 26, with the challenge to return to the Moon by 2024. Since that time, the HLS team has

- issued Next Space Technologies for Exploration Partnerships (NextSTEP) E for Human Landing System Studies, Risk Reduction, Development, and Demonstration, and selected 11 companies to conduct 17 studies and develop 25 prototypes;
- established the HLS program office at Marshall Space Flight Center and selected the program manager, Lisa Watson-Morgan;
- issued a final NextSTEP Broad Agency Announcement (BAA) (NextSTEP H) for the Human Landing System, after issuing two drafts and dispositioning more than 1,150 comments from industry before issuing the final BAA; and
- issued a request for information (RFI) for Artemis surface suits. The request sought ideas from industry for shifting surface suit production to the private sector following the in-house build for the 2024 landing mission.

Space Communications and Navigation (SCaN)

NASA's Space Communications and Navigation Program is responsible for leading the Agency's space communications and tracking through the management of its space communications networks, as well as developing advanced space communications and navigations technology. It also serves as the Agency's representative in domestic and international forums in the areas of spectrum management; space

communication architectures and data standards; and positioning, navigation, and timing policy. SCaN continued to lead the development of advanced space communication and navigation technology for the benefit of scientific and human exploration missions in near-Earth, deep space, and commercial space enterprises.

NASA operates and maintains three space communication networks—the Near Earth Network (NEN), Deep Space Network (DSN), and Space Network (SN)—composed of a ground network and its on-orbit Tracking and Data Relay Satellites (TDRSs). Consistent with prior years' successes, the three space communications networks provided approximately 252,644 tracking passes, while maintaining an extremely high proficiency level of 99 percent or better, above the 95 percent requirement. In this capacity, NASA served as a reliable partner to a wide range of external customers (other U.S. and international government agencies and commercial entities) for human exploration, robotic spaceflight launches, low-Earth and deep space science, and SmallSats (including CubeSats and NanoSats).

Astronauts and spacecraft depend on this reliable uplink and downlink of communications for the delivery of commands and essential crew instructions, as well as the retrieval of health and safety information and science data, with delivery of the data to individual mission control centers. During FY 2019, SCaN networks provided 24/7 global near-Earth and deep space communication and navigation (C&N) services to over 100 NASA programs and other U.S. Government entities, international civil space agencies, and commercial missions, including human spaceflight C&N requirements of the ISS. Several of these missions have more than one spacecraft, although these are counted as a single mission. Also, several missions are supported by more than one of the three networks; these are also counted as single missions. The networks provided launch and early-orbit telemetry, tracking, and communication (TT&C) services to 25 expendable launch vehicles (ELVs) in FY 2018.

The SN began working transition activities with customers in preparation for the completion of the Space Network Ground Segment Sustainment (SGSS) project. Activities included support to SGSS for project integration, testing, deployment, training, and transition to operations. In August 2019, the SN successfully transitioned TDRS-9 to SGSS to support Level 6 testing. Systems integration activities progressed, with SGSS completing a provisional acceptance testing that

determined whether the system met functionality and performance requirements, a key milestone before the initial Operations Readiness Review (ORR). SCaN's DSN Aperture Enhancement Project continued the addition of two 34-meter antennas at the Madrid Deep Space Communications Complex in Spain, which will increase the DSN's capacity.

NASA continued its leading role in coordinating the development of international space communication architectures and standards, which enable cross support and interoperability of systems. This work translates into reduced risk for missions and hundreds of millions of dollars in savings over a decade for NASA without reducing services and coverage for space missions. SCaN's Data Standards Manager was elected to serve as the chairman of the Management Council for the Consultative Committee for Space Data Systems (CCSDS), an international organization of 11 spacefaring nations chartered in 1982 to develop standards to solve common problems in the development and operation of space data systems. The CCSDS works closely with the Interagency Operations Advisory Group (IOAG) to ensure that standards are developed in coordination with Agency architecture plans and are responsive to Agency space missions. The IOAG is recognized as the international advisory body responsible for the coordination of cross support and interoperability for space communications, and it cooperates across the various international exploration forums focused on the coordination of future missions. As NASA's representative to the IOAG, SCaN engaged in key discussions and studies related to interoperability and cross support for future Moon and Mars missions, mission operations, optical communications, space internetworking, and other key issues. The IOAG takes guidance from the Interoperability Plenary (IOP), which includes representation from senior leadership of the IOAG agencies. The IOP met in December 2018 to review the progress of the IOAG since the last IOP meeting three years prior and to provide guidance for the coming years.

The Deep Space Atomic Clock (DSAC) was launched on the Orbital Test Bed spacecraft on June 25, 2019. With the DSAC onboard, a spacecraft traveling beyond Earth orbit will need only a one-way signal from Earth to navigate autonomously, which will free up valuable time on SCaN's Deep Space Network. DSAC also has a high degree of clock stability, meaning it can maintain its accuracy over

years. SCaN also completed a system critical design review for the Integrated Laser Communication Relay Demonstration (LCRD) Low-Earth Orbit User Modem and Amplifier Terminal (ILLUMA-T), which will be onboard the ISS and will communicate directly with LCRD.

SCaN worked within the CCSDS to release its first two industry standards for interoperable, free-space optical communications. Commonly known in the spacefaring community as Blue Books, the CCSDS Recommended Standards publications establish comprehensive technology standards for the international space community. These include highly detailed specifications for the manufacture and use of interfaces, technical capabilities and protocols, and other controlling standards such as encoding regimes. This is the culmination of a multi-year standardization effort in CCSDS, with active participation from NASA, ESA, the Centre National d'Études Spatiales (CNES), DLR, JAXA, and others. The standard is designed for photon-starved free space optical communications, as occurs for missions to deep space, the Moon, and low-power Earth orbiting missions. Initial demonstrations of this technology will be hosted by NASA's Psyche and Orion spacecraft.

SCaN continued to serve as the Agency's spectrum manager, with responsibility for representing NASA's spectrum interests and negotiating on its behalf with the White House, Congress, relevant Government agencies and national regulators, and interagency partners in the determination of spectrum allocations. As part of the U.S. delegation, SCaN participated in the World Radiocommunication Conference (WRC-19), concluding in November 2019. WRC-19 set protection levels for science and weather systems operating in the 24-GHz band that balanced the needs of both the scientific and the commercial uses of the spectrum. The adopted regulations support the acquisition of data used for weather prediction, science, and public safety while also allowing the development and deployment of 5G technologies. The U.S. regulators have expressed commitment to resolving any reported interference regardless of the point in time the interference occurs. NASA has initiated efforts to monitor any potential impact of 5G systems and is committed to working with regulators and industry to facilitate sharing.

SCaN continued leading NASA's efforts in U.S. interagency and International Positioning, Navigation, and Timing (PNT) Policy Management. Since 2007, it

has sponsored the National Space-Based PNT Advisory Board and an independent Federal Advisory Committee Act (FACA) board and, as Executive Director, coordinated the National Space-Based PNT Advisory Board's biannual sessions. Its success led the NASA Administrator, in 2019, to appoint a SCaN employee as Executive Secretary of the National Space Council (NSpC) Users' Advisory Group (UAG), another FACA board. The UAG held its fourth meeting in October 2019, during which it approved four key recommendations and identified critical areas for cooperation with the PNT Advisory Board in protecting Global Positioning System (GPS) space users from harmful interference. NASA continued assisting the USAF with the implementation of GPS Block IIIF, the next batch of 22 GPS satellites, to protect and improve GPS capabilities to support space users. Efforts include 1) preserving current navigation capabilities within the Space Service Volume (SSV), the region of space between LEO and Geosynchronous Earth Orbit (GEO); 2) implementing Laser Retro-reflector Arrays (LRAs) to enable high-precision measurements; and 3) implementing Canadian-furnished GPS Search and Rescue (GPS SAR) payloads. NASA continued working with foreign Global Navigation Satellite System (GNSS) service providers to develop an Interoperable Multi-GNSS SSV that will expand the PNT capabilities beyond what any one GNSS can provide on its own. This included coordinating U.S. efforts at the United Nations to develop the booklet "The Interoperable GNSS SSV" (first edition), released in November 2018, an international baseline to use GPS/GNSS for mission planners in space agencies and commercial space. NASA also began work on a second edition for release in 2020–21, which will further improve the analyses and expand the scope beyond GEO altitude and into lunar space. Other efforts include the development of the international GNSS-based Medium Earth Orbit Search and Rescue (MEOSAR), of which GPS SAR is the U.S. contribution, to locate emergency beacons. Key events in FY 2019 included 1) qualifying the emergency location beacon for the Orion crew life-preserver units; 2) tracking the emergency location signals during the October 11, 2018, Soyuz launch abort; and 3) assisting the U.S. CCP in implementing SAR beacons.

Science Mission Directorate

NASA's Science Mission Directorate (SMD) explores scientific questions about Earth, the Sun, our solar system, and the universe beyond. NASA works with our partners and the science community at large to collect data and conduct experiments with our air, space, and ground-based observatories. In fiscal year 2019, SMD operated more than 65 missions through the four SMD science divisions (Earth Science, Planetary Science, Heliophysics, and Astrophysics), along with the Joint Agency Satellite Division and the James Webb Space Telescope Program Office.

The research that SMD conducts provides critical insights into Earth and space systems that increase societal benefits across the globe. Earth-observing satellites allow us to track severe weather and observe Earth's changing climate. SMD's space-based observatories have explored our solar system and beyond, identifying exoplanets and the first sign of a moon outside our solar system. Our heliophysics observatory studies the fundamental nature of space around Earth and throughout our solar system—a system driven by the constant outflow of energy and material from the Sun. Finally, planetary missions have researched Mars's seismic activity and orbited the asteroid Bennu in an effort to understand how our solar system's planets originally formed and how life began.

Earth Science

The Earth Science Division (ESD) used observations from satellites, instruments on the International Space Station (ISS), airplanes, balloons, ships, and land to collect data about the science of our planet's atmospheric motion and composition; land cover, land use, and vegetation; ocean currents, temperatures and upper-ocean life; and ice on land and sea. The four program elements of ESD design the science and technology, launch airborne and space missions, analyze the data and observations, and develop ways to put the information to use for societal benefit. More than collecting the data, ESD works with Government and commercial partners in the United States and internationally to put that unique information to work as we explore our home planet, improve lives, and safeguard the future for people all over the world. Earth science research also helps advance

space exploration by helping scientists recognize the basic markers for life across the universe.

In FY 2019, ESD launched multiple science investigations to the ISS. The Global Ecosystem Dynamics Investigation (GEDI) was one such instrument and arrived at the ISS on December 8, 2018. It provides high-quality laser ranging observations of Earth's forests and topography required to advance the understanding of important carbon- and water-cycling processes, biodiversity, and habitat. GEDI is mounted on the Japanese Experiment Module's Exposed Facility and provides the first high-resolution observations of forest vertical structure at a global scale. These observations will quantify the aboveground carbon stored in vegetation and changes that result from vegetation disturbance and recovery, the potential for forests to sequester carbon in the future, and habitat structure and its influence on habitat quality and biodiversity.

Another science instrument to recently arrive at the ISS was the Orbiting Carbon Observatory–3 (OCO-3), which arrived in May 2019. OCO-3 examines the complex dynamics of Earth's atmospheric carbon cycle by collecting measurements to track variations in a specific type of atmospheric carbon dioxide. OCO-3 is also contributing to focused studies of how space-based measurements can constrain rapidly changing anthropogenic (humanmade) emissions. Anthropogenic emissions could be the largest source of uncertainty in the global carbon budget. OCO-3 measurements help reduce the uncertainty of natural fluxes. Understanding carbon sources can aid in forecasting increased atmospheric heat retention and reduce its long-term risks.

ESD is seeing great science returns from the recently launched Ice, Cloud and land Elevation Satellite–2 (ICESat-2). The satellite is measuring the height of sea ice to within an inch, tracing the terrain of previously unmapped Antarctic valleys, surveying remote ice sheets, and peering through forest canopies and shallow coastal waters. With each pass of the ICESat-2 satellite, the mission adds to datasets tracking Earth's rapidly changing ice. Researchers are ready to use the information to study sea-level rise resulting from melting ice sheets and glaciers and to improve sea ice and climate forecasts.

Through technology development, research, and development of new applications, NASA's Earth Science program enhances our fundamental understanding

of our home planet and improved everyday life on Earth. Below are a few research highlights from FY 2019.

NASA-Created Map Saves $1.2 Million in Staff Time

A NASA-created map that consolidated 26 different postfire datasets can now do in minutes what used to take Federal, state, and local agencies 800 hours to compile. In 2018, a record year for fires, this map saved those agencies the equivalent of more than $1.2 million in staff time. An online, postfire decision-support tool that quickly provides important information for response teams in the wake of a fire, the map shows where a fire's aftermath leaves an area vulnerable to debris flow, flooding, erosion, and landslides. The map is called Rehabilitation Capability Convergence for Ecosystem Recovery (RECOVER), created by Keith Weber, an investigator supported by the NASA Earth Applied Sciences Disasters Program.

International Team Makes Unexpected Discovery Under Greenland Ice

An international team of researchers, including a NASA glaciologist, has discovered a large meteorite impact crater hiding beneath more than a half mile of ice in northwest Greenland. The crater—the first of any size found under the Greenland ice sheet—is one of the 25 largest impact craters on Earth, measuring roughly 1,000 feet deep and more than 19 miles in diameter, an area slightly larger than that inside Washington's Capital Beltway.

NASA Provides New Look at Puerto Rico Post–Hurricane Maria

When Hurricane Maria struck Puerto Rico head-on as a Category 4 storm with winds of up to 155 miles per hour in September 2017, it damaged homes, flooded towns, devastated the island's forests, and caused the longest electricity blackout in U.S. history. Two new NASA research efforts delve into Hurricane Maria's far-reaching effects on the island's forests as seen in aerial surveys and on its residents' energy and electricity access as seen in data from space. The findings illustrate the staggering scope of Hurricane Maria's damage to both the natural environment and communities.

More Glaciers in East Antarctica Are Waking Up

East Antarctica has the potential to reshape coastlines around the world through sea-level rise, but scientists have long considered it more stable than its neighbor, West Antarctica. Now, new detailed NASA maps of ice velocity and elevation show that a group of glaciers spanning one-eighth of East Antarctica's coast have begun to lose ice over the past decade, hinting at widespread changes in the ocean.

Joint Agency Satellite Division (JASD)

The Joint Agency Satellite Division is an organization within NASA's Science Mission Directorate with broad cross-cutting responsibilities. In partnership with the National Oceanic and Atmospheric Administration (NOAA), JASD manages the development and launch of environmental satellite programs, projects, and instruments on a reimbursable basis.

Heliophysics

The Heliophysics Division (HPD) studies the Sun and how it influences the very nature of space, planets, and the entire solar system. By studying key space phenomena and processes—many of which are driven by the constant outflow of energy and material from our Sun—heliophysics research supports situational awareness to better protect astronauts, satellites, and robotic missions traveling through the solar system. To gather such crucial insights, Heliophysics missions explore places never before visited: right into the Sun itself, into pockets of intense radiation near Earth, and past the planets into interstellar space.

Understanding space weather is a key area of research for heliophysics. Space weather is a naturally occurring phenomenon with the potential to substantially disrupt or damage technological systems, including communication and navigation systems, the electric power grid, and space launch and satellite operations, as well as adversely impact the health of humans in space and passengers and crew in high-altitude aircraft.

Reducing the Nation's vulnerability to space weather has been identified as a national priority and necessitates the development of improved capabilities to

understand and mitigate the associated hazards. The HPD's Space Weather Science Application (SWxSA)—called for by the 2019 National Space Weather Strategy and Action Plan—seeks to improve understanding of our complex space environment and enhance capabilities that protect and mitigate space weather impacts on life, society, infrastructure, and space exploration. SWxSA makes observations from space and develops models that directly advance the space weather forecasting capability that the Nation requires in partnership with NOAA, the U.S. Air Force, the NSF, and other collaborators as needed. Additionally, SWxSA supports NASA's Artemis program to help protect human explorers as we move forward to the Moon and to Mars.

To study the very source of the outpouring of solar material that drives space weather, NASA launched Parker Solar Probe, a "Mission to Touch the Sun," in August 2018. Parker completed its first perihelion, or closest approach to the Sun, in November 2018. The primary science goals for the mission are to trace the flow of energy and understand the heating of the solar corona and to explore what accelerates the solar wind. The outflow of material from the solar wind fills up the inner part of our solar system, creating a bubble that envelops the planets and extends far past the orbit of Neptune. Embedded in the solar wind's energized particles and solar material is the Sun's magnetic field. Additional one-off eruptions of solar material called coronal mass ejections also carry this solar magnetic field—and in both cases, this magnetized material can interact with Earth's natural magnetic field and cause geomagnetic storms. Such storms can trigger the aurora or even power outages, and other types of solar activity can cause communications problems, disrupt satellite electronics, and even endanger astronauts—especially beyond the protective bubble of Earth's magnetic field. After the spacecraft's second solar encounter, Parker Solar Probe transmitted 22 gigabytes of science data collected during the first two encounters to the mission team at the Johns Hopkins Applied Physics Laboratory (APL) in Laurel, Maryland. Parker will provide new data on solar activity and make critical contributions to our ability to forecast major space-weather events that impact life on Earth.

To better understand how space weather can impact technology aboard missions, NASA also recently launched technology demonstrations in June 2019, as a rideshare on a U.S. Air Force mission, to look at the space environment around

Earth and how it affects our technology. Four NASA experiments make up the Space Environment Testbeds (SET), which began transmitting data in November 2019. SET aims its sights on a part of near-Earth space called the slot region: the gap between two of Earth's vast radiation belts, also known as the Van Allen belts. The doughnut-shaped Van Allen belts seethe with radiation trapped by Earth's magnetic field. Where SET orbits is thought to be calmer but known to vary during extreme space weather storms driven by the Sun. How much it changes exactly, and how quickly, remains uncertain. The slot region is an attractive one for satellites—especially navigation and communications satellites—because from about 12,000 miles up, it offers not only a relatively friendly radiation environment, but also a wide view of Earth. During intense magnetic storms, however, energetic particles from the outer belt can surge into the slot region. SET surveys the slot region, providing some of the first day-to-day weather measurements of this particular neighborhood in near-Earth space. The mission also studies the fine details of how radiation damages instruments and tests different methods to protect them, helping engineers build parts better suited for spaceflight.

Heliophysics missions also seek to understand the fundamental characteristics of our space environment to better understand how our solar system fits in and is affected by our galaxy. On November 5, 2018, for the second time in history, a humanmade object reached the space between the stars. Following Voyager 1, NASA's Voyager 2, launched in 1977, exited the heliosphere—the protective bubble of particles and magnetic fields created by the Sun. Comparing data from different instruments aboard the trailblazing spacecraft, mission scientists determined that the spacecraft had successfully crossed the outer edge of the heliosphere. This boundary, called the heliopause, is where the tenuous, hot solar wind meets the cold, dense interstellar medium. Voyager 2 carries a working instrument that will continue to provide pioneering observations of the next frontier—interstellar space.

Voyager 2 is not yet in undisturbed interstellar space: like its twin, Voyager 1, Voyager 2 appears to be in a perturbed transitional region just beyond the heliosphere. There, the spacecraft continue to send back information about how the solar wind interacts with interstellar space. We are, for the very first time, getting a glimpse of the intergalactic neighborhood beyond the magnetic reach of our

star—information that both helps inform other astrophysics observations of much more distant regions and provides information that could ultimately help us safely explore even further beyond our own home.

The two Voyager spacecraft are the most distant sentinels from Earth. Together, they provide a detailed glimpse of how our heliosphere interacts with the constant interstellar wind flowing from beyond. Their observations complement data from NASA's Interstellar Boundary Explorer (IBEX), a mission to remotely sense that boundary. NASA also is preparing the upcoming Interstellar Mapping and Acceleration Probe (IMAP)—due to launch in 2024—to capitalize on the Voyagers' observations.

The Geospace Dynamics Constellation (GDC) Science and Technology Definition Team (STDT) delivered their final report, which describes a focused mission concept that would address gaps in key scientific questions about Earth's upper atmosphere (called the ionosphere-thermosphere). When energy from the magnetosphere enters the polar ionosphere-thermosphere, it drives dynamics and processes that affect the entire upper atmosphere. These driven processes have real effects on national capabilities through interference with communication and navigation, radiation damage of spacecraft systems, and other mechanisms. Further, these processes at Earth are also present at Mars, and robotic and human exploration at that planet are affected by similar issues. A robust investigation and scientific understanding of this system at Earth will enable and enhance the Agency's and the Nation's ability to forecast and mitigate these damaging effects.

In addition to supporting key spacefaring missions, HPD directly supports research. The Heliophysics Research Program supports technology development and scientific investigation to achieve a program of excellence. The research program highlights the newest mission data, utilizes the latest advances in modeling and machine learning, and develops the most innovative technological solutions to improve our understanding of the Sun and its effects on Earth and other planets in our solar system. Below are a few research highlights from FY 2019.

Pressure Runs High at Edge of Solar System

Using observations of galactic cosmic rays—a type of highly energetic particle—from NASA's Voyager spacecraft, scientists calculated the total pressure from

particles in the outer region of the solar system, known as the heliosheath. At nearly 9 billion miles away, this region is hard to study. The unique positioning of the Voyager spacecraft and the opportune timing of a solar event made measurements of the heliosheath possible. The results are helping scientists understand how the Sun interacts with its surroundings.

THEMIS-ARTEMIS Gains Insight on the Moon's Environment

The multi-spacecraft Heliophysics explorer mission Time History of Events and Macroscale Interactions during Substorms (THEMIS) has two of its spacecraft orbiting the Moon; the pair is called THEMIS-ARTEMIS (Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun). The Moon possesses a very tenuous atmosphere: ionization of this atmosphere, primarily by sunlight, creates a lunar ionosphere roughly one million times more tenuous than that of Earth. When the Moon passes through the near vacuum of the geomagnetic tail of Earth each lunar month around the full Moon, the lunar-derived charged-particle density becomes comparable to the ambient value, and the presence of the lunar ionosphere can affect its surroundings. This can lead to better characterization of the lunar environment in anticipation of future human exploration of our closest planetary body.

Streaks in Aurora Found to Map Features in Earth's Radiation Environment

A special kind of streaked aurora has been found to track disturbances in near-Earth space from the ground. Known as structured diffuse aurora, it was recently discovered, with the help of NASA spacecraft and instruments, that these faint lights in the night sky can map the edges of the Van Allen radiation belts—hazardous concentric bands of charged particles encircling Earth. When the Van Allen belts undulate in shape and size—which they do in response to incoming radiation from the Sun as well as changes from Earth below—they can envelop satellites in unexpected radiation. The new discovery will help us better track the edges of the belts—and the more we know about how the belts are changing, the more we can mitigate such effects.

NASA's Magnetospheric Multiscale Mission Finds Its First Interplanetary Shock

The Magnetospheric Multiscale (MMS) mission has spent the past four years using high-resolution instruments to see what no other spacecraft can. Recently, MMS made the highest-resolution measurements ever of an interplanetary shock. These shocks, made of particles and electromagnetic waves, are launched by the Sun. As they roll outward, they drive change throughout our space environment, so they are a classic example of the structures we are better trying to understand in our heliosphere. MMS's view right from within the shock provides insight into a phenomenon that we rarely are able to study directly.

How Scientists Used NASA Data to Predict the Appearance of July 2 Eclipse

Heliophysics relies not only on observations, but on making use of such data to create cutting-edge models and simulations. Ultimately, such simulations can lead to improvements in our ability to predict the Sun's activity and incoming space weather—thus protecting satellites, astronauts, and communications systems such as radio and GPS. Eclipses are a key opportunity to test such predictive models, as they provide crisp views from the ground of the solar atmosphere. Predictive Science, Inc.—a private computational physics research company based in San Diego, California, and supported by NASA, the National Science Foundation, and the Air Force Office of Scientific Research—used data from NASA's Solar Dynamics Observatory (SDO), New Mexico State University, and the National Solar Observatory to develop a prediction of what the corona would look like during the July 2, 2019, eclipse. By comparing their prediction to eclipse photographs from the ground, the researchers could assess and improve the performance of their models. The researchers' prediction features a nebulous corona with two wide, hazy streamers opposite each other, as well as smaller plumes sprouting out of the north and south magnetic poles. The team was pleased to see a close match to their predictions and continues to work on improving their models further.

Planetary Science

NASA's Planetary Science Division (PSD) is engaged in one of the oldest of scientific pursuits: the observation and discovery of our solar system's planetary

objects. We undertake this enterprise in order to better understand the history of our solar system and the distribution of life within it. For decades, NASA's planetary science program has advanced the scientific understanding of the solar system in extraordinary ways while pushing the limits of spacecraft and robotic engineering design and operations. PSD continues to expand our knowledge of the solar system, with spacecraft that have visited every planet as well as a variety of small bodies (e.g., asteroids, comets, dwarf planets, etc.), including those at the very edge of our solar system.

One of the most successful and enduring feats of interplanetary exploration, NASA's Opportunity rover mission ended after almost 15 years of exploring the surface of Mars. Opportunity stopped communicating with Earth when a severe Martian global dust storm blanketed its location in June 2018. After more than a thousand commands to restore contact, engineers at NASA's Jet Propulsion Laboratory (JPL) ceased attempts to revive Opportunity in February 2019. Designed to last just 90 Martian days and travel 1,100 yards (1,000 meters), Opportunity vastly surpassed all expectations in its endurance, scientific value, and longevity. In addition to exceeding its life expectancy by 60 times, the rover traveled more than 28 miles (45 kilometers) by the time it reached its final resting spot on Mars—aptly named Perseverance Valley.

During its lifetime, Opportunity contributed tremendously to Mars exploration. It returned more than 217,000 images, including 15 360-degree color panoramas. It exposed the surfaces of 52 rocks to reveal fresh mineral surfaces for analysis and cleared 72 additional targets with a brush to prepare them for inspection with spectrometers and a microscopic imager. Opportunity also found hematite, a mineral that forms in water, at its landing site. Furthermore, it discovered strong indications at Endeavour Crater of the action of ancient water similar to the drinkable water of a pond or lake on Earth.

Following in Opportunity's tracks, NASA's Curiosity rover continues to explore Mars after having touched down over seven years ago. It has traveled a total of 13 miles (21 kilometers) and ascended 1,207 feet (368 meters) to its current location. Along the way, Curiosity has enabled many important scientific discoveries, including the finding that Mars had the conditions to support microbial life in its ancient past.

In November 2018, NASA's Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) lander successfully touch down on Mars. InSight's primary objective is to collect data on the Martian interior with instruments intended to measure "Marsquakes." On April 6, 2019, the lander's Seismic Experiment for Interior Structure (SEIS) instrument detected a faint seismic signal. This was the first recorded trembling that appears to have come from inside the planet, as opposed to being caused by forces above the surface, such as wind. The Martian surface is extremely quiet, allowing SEIS, InSight's specially designed seismometer, to pick up faint rumbles. By studying the deep interior of Mars, scientists hope to learn how other rocky worlds, including Earth and the Moon, formed.

Detecting these tiny quakes required a huge feat of engineering. On Earth, high-quality seismometers often are sealed in underground vaults to isolate them from changes in temperature and weather. InSight's instrument has several ingenious insulating barriers, including a cover built by JPL called the Wind and Thermal Shield, to protect it from the planet's extreme temperature changes and high winds.

Also in November 2018, the NASA Dawn mission ended after traveling approximately 4.3 billion miles (6.9 billion kilometers) since its launch 11 years ago. Propelled by ion engines, the spacecraft achieved many firsts along the way. In 2011, when Dawn arrived at Vesta, the second largest body in the main asteroid belt, the spacecraft became the first to orbit a body in the region between Mars and Jupiter. In 2015, when Dawn went into orbit around Ceres, a dwarf planet that is also the largest body in the asteroid belt, the mission became the first to visit a dwarf planet and go into orbit around two destinations beyond Earth. The data Dawn sent back to Earth from its four science experiments enabled scientists to compare two planet-like worlds that evolved very differently. Among its accomplishments, Dawn showed how important location was to the way objects in the early solar system formed and evolved. Dawn also reinforced the idea that dwarf planets could have hosted oceans over a significant part of their history—and potentially still do.

In December 2018, NASA's Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer (OSIRIS-REx) spacecraft completed its 1.2-billion-mile (2-billion-kilometer) journey to arrive at the asteroid Bennu. Upon arrival, OSIRIS-REx began a series of flybys of the asteroid to refine estimates of Bennu's mass and spin rate and to generate a more precise model of its shape. The

reconnaissance data were then used to select four potential sites for samples to be collected for later return to Earth. The OSIRIS-REx mission will help scientists investigate how planets formed and how life began and will improve our understanding of asteroids that could impact Earth. OSIRIS-REx is also setting new records for the smallest body ever orbited by a spacecraft and the closest orbit of a planetary body by any spacecraft.

Shortly after arriving at Bennu, data from OSIRIS-REx revealed the presence of molecules that contain oxygen and hydrogen atoms bonded together, known as "hydroxyls." The team suspects that these hydroxyl groups exist globally across the asteroid in water-bearing clay minerals, meaning that at some point, Bennu's rocky material interacted with water. While Bennu itself is too small to have ever hosted liquid water, the finding does indicate that liquid water was present at some time on Bennu's parent body, a much larger asteroid.

The Juno spacecraft, which entered orbit around Jupiter in July 2016, successfully completed its 21st science pass of the gas giant at the end of FY 2019 and has performed more than half of its planned orbits. During flybys, Juno's suite of sensitive science instruments probes beneath the planet's obscuring cloud cover and studies Jupiter's auroras to learn more about the planet's origins, interior structure, atmosphere, and magnetosphere. To date, Juno has provided complete, global coverage of Jupiter and detected atmospheric wave trains, towering atmospheric structures that trail one after the other as they roam the planet, at smaller distances between individual wave crests than ever seen before. These data provide valuable information on both the dynamics of Jupiter's atmosphere and its structure in the regions underneath the waves.

NASA's PSD uses an array of spacecraft to help us understand our solar system and the potential for life elsewhere, and it undertakes efforts to understand and prepare for potentially hazardous near-Earth objects (NEOs). Below are several research highlights from FY 2019.

NASA's Juno Finds Changes in Jupiter's Magnetic Field

NASA's Juno mission to Jupiter made the first definitive detection beyond our world of an internal magnetic field that changes over time, a phenomenon called secular variation. Juno determined that the gas giant's secular variation is most

likely driven by the planet's deep atmospheric winds. The discovery will help scientists further understand Jupiter's interior structure—including atmospheric dynamics—as well as changes in Earth's magnetic field.

NASA's Curiosity Mars Rover Finds a Clay Cache

NASA's Curiosity rover has confirmed that the region on Mars that it is exploring, called the "clay-bearing unit," is well deserving of its name. Two samples the rover recently drilled at rock targets called "Aberlady" and "Kilmarie" have revealed the highest amounts of clay minerals ever found during the mission. Clay often forms in water, which is essential for life; Curiosity is exploring Mount Sharp to see if it had the conditions to support life billions of years ago. Other than proof that there was a significant amount of water once in Gale Crater, what these new findings mean for the region is still up for debate. It is likely that the rocks in the area formed as layers of mud in ancient lakes—something Curiosity also found lower on Mount Sharp.

New Horizons Spacecraft Returns Its Sharpest Views of 2014 MU69

Images of the Kuiper Belt Object Arrokoth (previously known as 2014 MU69)—obtained by the New Horizons telephoto Long-Range Reconnaissance Imager (LORRI) on January 1, 2019—offered a resolution of about 110 feet (33 meters) per pixel. The combination of high spatial resolution and a favorable viewing angle gave the team an unprecedented opportunity to investigate the surface as well as the origin and evolution of Arrokoth, which is thought to be the most primitive object ever encountered by a spacecraft.

Astrophysics

NASA's Astrophysics Division (APD) studies the universe. APD seeks to understand the universe and our place in it and to investigate the origin of the universe and the full history of stars and galaxies. Through APD, NASA is discovering how planetary systems form around other stars and searches for environments hospitable for life to develop. APD searches for the signature of life on other worlds, perhaps to learn that we are not alone.

After nine years in deep space collecting data that indicate that our sky is filled with billions of hidden planets—more planets even than stars—NASA's Kepler space telescope has run out of the fuel needed for further science operations. Kepler has opened our eyes to the diversity of planets that exist in our galaxy. The most recent analysis of Kepler's discoveries concludes that 20 to 50 percent of the stars visible in the night sky are likely to have small, possibly rocky, planets similar in size to Earth and located within the habitable zone of their parent stars. That means that they are located at distances from their parent stars where liquid water—a vital ingredient to life as we know it—might pool on the planet's surface.

Before retiring the spacecraft, scientists pushed Kepler to its full potential, successfully completing multiple observation campaigns and downloading valuable science data even after initial warnings of low fuel. The latest Kepler data, from Campaign 19, will complement the data from NASA's newest planet hunter, the Transiting Exoplanet Survey Satellite (TESS), launched in April 2018. TESS builds on Kepler's foundation in its search of planets orbiting some 200,000 of the brightest and nearest stars to Earth, worlds that can later be explored for signs of life by future missions, such as NASA's James Webb Space Telescope (JWST).

TESS has discovered three new worlds orbiting TESS Object of Interest (TOI) 270, an M-type dwarf star about 40 percent smaller than the Sun in both size and mass. One of the exoplanets is slightly larger than Earth, and the other two are of a type not found in our solar system. The planets straddle an observed gap in the sizes of known planets and promise to be among the most curious targets for future studies.

The innermost planet, TOI 270 b, is likely a rocky world about 25 percent larger than Earth. It orbits the star every 3.4 days at a distance about 13 times closer than Mercury orbits the Sun. Based on statistical studies of known exoplanets of similar size, the science team estimates that TOI 270 b has a mass around 1.9 times greater than Earth's. The other two planets, TOI 270 c and d, are, respectively, 2.4 and 2.1 times larger than Earth and orbit the star every 5.7 and 11.4 days. Although only about half its size, both may be similar to Neptune in our solar system, with compositions dominated by gases rather than rock, and they likely weigh around seven and five times Earth's mass, respectively. Further research may reveal additional planets beyond the three now known. If planet d has a rocky core covered by a

thick atmosphere, its surface would be too warm for the presence of liquid water, considered a key requirement for a potentially habitable world.

In FY 2019, using NASA's Hubble and Kepler space telescopes, astronomers uncovered evidence of what could be the first discovery of a moon orbiting a planet outside our solar system. This moon candidate, which is 8,000 light-years from Earth in the Cygnus constellation, orbits a gas-giant planet that, in turn, orbits a star called Kepler-1625. Researchers caution that the moon hypothesis is tentative and must be confirmed by follow-up Hubble observations. Since moons outside our solar system, known as exomoons, cannot be imaged directly, their presence is inferred when they pass in front of a star, momentarily dimming its light. Such an event is called a transit and has been used to detect many of the exoplanets catalogued to date.

Hubble also recently helped reveal magnesium and iron gas streaming from a strange world outside our solar system known as WASP-121b. The observations represent the first time that so-called "heavy metals" (elements heavier than hydrogen and helium) have been spotted escaping from a so-called "hot Jupiter," a large, gaseous exoplanet very close to its star. This exoplanet is orbiting so dangerously close to its star that its upper atmosphere reaches a blazing 4,600 degrees Fahrenheit. The observations of WASP-121b add to the developing story of how planets lose their primordial atmospheres. When planets form, they gather an atmosphere containing gas from the disk in which the planet and star formed. These atmospheres consist mostly of the primordial, lighter-weight gases hydrogen and helium, the most plentiful elements in the universe. This atmosphere dissipates as a planet moves closer to its star.

In August 2019, NASA reached a major milestone when engineers successfully connected the two halves of NASA's JWST for the first time at Northrop Grumman's facilities in Redondo Beach, California. Once it reaches space, NASA's most powerful and complex space telescope will explore the cosmos—from planets and moons within our solar system to the earliest and most distant galaxies—using infrared light.

NASA's APD has advanced our understanding of our universe and the search for life on other planets through FY 2019. Below are some research highlights.

NASA's Hubble Finds Water Vapor on Habitable-Zone Exoplanet for First Time

Its size and surface gravity are much larger than Earth's, and its radiation environment may be hostile, but a distant planet called K2-18b has captured the interest of scientists all over the world. For the first time, researchers have detected water vapor signatures in the atmosphere of a planet beyond our solar system that resides in the "habitable zone," the region around a star in which liquid water could potentially pool on the surface of a rocky planet.

In Search of Missing Worlds, Hubble Finds a Fast-Evaporating Exoplanet

Astronomers have been perplexed in conducting a census of star-hugging extrasolar planets. They have found hot Jupiter-sized planets and hot super-Earths (planets no more than 1.5 times Earth's diameter). These planets are scorching hot because they orbit very close to their stars. But so-called "hot Neptunes," whose atmospheres are heated to more than 1,700 degrees Fahrenheit, have been much harder to find. In fact, only about a handful of "hot Neptunes" have been found so far. Uncovering two evaporating "warm Neptunes" reinforces the idea that the hotter version of these distant worlds may be a class of transitory planet whose ultimate fate is to shrink down to the most common type of known exoplanet, "mini-Neptunes"—planets with heavy, hydrogen-dominated atmospheres that are larger than Earth but smaller than Neptune. Eventually, these planets may downsize even further to become super-Earths—more massive, rocky versions of Earth.

Confirmation of Toasty TESS Planet Leads to Surprising Find of Promising World

A piping-hot planet discovered by NASA's TESS has pointed the way to additional worlds orbiting the same star, one of which is located in the star's habitable zone. If made of rock, this planet may be around twice Earth's size.

NASA's Fermi Traces the History of Starlight Across the Cosmos

One of the main goals of the Fermi mission, which celebrated its 10th anniversary in orbit this year, was to assess the extragalactic background light (EBL), a cosmic fog composed of all the ultraviolet, visible, and infrared light stars have created over the universe's history. Because starlight continues to travel across the cosmos long after its sources have burned out, measuring the EBL allows

astronomers to study stellar formation and evolution separately from the stars themselves. Scientists using data from NASA's Fermi Gamma-ray Space Telescope have measured all the starlight produced over 90 percent of the universe's history. The analysis, which examines the gamma-ray output of distant galaxies, estimates the formation rate of stars and provides a reference for future missions that will explore the still-murky early days of stellar evolution.

Aeronautics Research Mission Directorate

During FY 2019, NASA's Aeronautics Research Mission Directorate (ARMD) worked to explore safe advances in atmospheric flight that directly benefit U.S. taxpayers, meet the rapidly evolving needs of industry, spark economic growth, and ensure that the Nation remains the world's leader in all things related to flight operations and aeronautical innovation.

With a wide-ranging research portfolio informed by a comprehensive Strategic Implementation Plan aimed at transforming aviation for the 21st century, NASA's flight team during FY 2019 focused on goals in three broad areas requiring scientific and engineering investigations:

- Enabling a new market for commercial supersonic air travel over land with the help of data gathered by the X-59 Quiet SuperSonic Technology (QueSST) airplane, which was fully under construction during FY 2019 and targeted to make its first flight in FY 2021.
- Leading industry in developing the technology and systems to safely enable Advanced Air Mobility: the use of new and novel aircraft, from small delivery drones to passenger-carrying vehicles, anywhere within the National Airspace System—from small communities to large metropolitan areas—to conduct missions including civic resource management, package delivery, and intraregional passenger transportation.
- Reducing emissions, minimizing noise, and shrinking reliance on fossil fuels in large part by studying electrically driven methods of propulsion on aircraft, including the X-57 Maxwell, which is serving as a testbed for solving the challenges of integrating a fully electric propulsion system on a general aviation-sized airplane.

In pursuing these goals and many others—including supplying technical solutions to the Federal Aviation Administration (FAA) for its Next Generation Air Transportation System—NASA's aeronautical innovators joined their talents in partnership with the brightest aviation experts within Government, industry, and academia.

Quiet Supersonic Flight Over Land

Project teams from ARMD's Advanced Air Vehicles Program and Integrated Aviation Systems Program during FY 2019 made steady progress with the Low-Boom Flight Demonstration mission, which seeks to enable the possibility of boarding a commercial supersonic airliner and flying across the United States in half the time. To do this, NASA is building the X-59 QueSST airplane, whose unique shape and technology are designed to turn the loud sonic booms currently associated with faster-than-sound flight into barely perceptible sonic thumps. The X-59 will be flown above select U.S. communities to measure and record public response to its noise while flying supersonic. The resulting statistically valid data will be presented to rulemakers, who will then consider lifting the ban—in place since 1973—on supersonic flight over land.

Early in FY 2019, NASA researchers deployed to Galveston, Texas, to fly an F/A-18 supersonic jet near the city in a way that simulates the quieter sonic booms expected from the X-59. Trial methods for gathering public perception of the sound were tested and experienced gains in managing public awareness before, during, and after the two-week-long exercise. Meanwhile, construction of the X-59 by Lockheed Martin Aeronautics Company in Palmdale, California, continued in earnest as the project passed its Critical Design Review. By the end of FY 2019, the airplane was under construction on the factory floor.

More information is available at the following locations:

- *https://www.nasa.gov/feature/nasa-goes-quiet-over-galveston-for-flight-series*
- *https://www.nasa.gov/aero/nasa-supersonic-x59-quesst-coming-together-at-famed-factory*
- *https://www.nasa.gov/subject/7566/supersonic-flight/*

Advanced Air Mobility

As the proliferation of drones, both commercial and recreational, continued to fill the skies and dominate discussions about the future of aviation not only in the United States but around the world, NASA's aeronautical innovators kept pace with their role as leaders in the area of Advanced Air Mobility (AAM) during FY 2019.

A key accomplishment took place over the cities of Corpus Christi, Texas, and Reno, Nevada, as NASA and its Government, industry, and academic partners wrapped up the final of four aerial demonstrations of the Unmanned Aircraft Systems Traffic Management (UTM) system. These demonstrations—known as Technical Capability Levels (TCLs)—began in FY 2015 and involved increasingly complex scenarios under which pilots operated their drones and coordinated their activities with others using UTM. For this final set of demonstrations (TCL-4), during FY 2019, pilots flew their drones in and around the dense urban environment of the two cities, successfully exercising the systems required to support the activity and paving the way for the passenger- and cargo-carrying AAM flight activities to come.

After hosting an industry conference and seeking input from a number of sources throughout the FY 2019, NASA laid the foundation for conducting a series of AAM-related events known as the National Campaign (formerly Grand Challenge), the first of which is targeted for FY 2022. The purpose of the Grand Challenge is to promote confidence in advanced air mobility systems and help organizations and companies learn what it really takes to operate air vehicles safely in an urban environment. The Grand Challenge is a series of increasingly complex field demonstrations that will support the FAA in developing an approval process for AAM vehicle certification; develop flight operations guidelines; evaluate requirements for communications, navigation, and surveillance; characterize vehicle noise levels; and define airspace operations management activities.

More information is available at the following locations:

- *https://www.nasa.gov/ames/presskit/utmcorpus*
- *https://www.nasa.gov/centers/armstrong/features/UrbanAirMobilityGrandChallenge.html*
- *https://www.nasa.gov/uam*

Electrified Aircraft Propulsion

With global interest in reducing aviation's impact on the environment, NASA researched developing technologies and systems that could be incorporated into future airplanes whose propulsion is powered by electricity. Much of the research into electrified aircraft propulsion centered on testing and preparing the all-electric X-57 Maxwell for its initial flight tests still ahead.

For example, engineers studied an innovative way to cool the heat generated by the electronics associated with the X-57's electric motors. This was done by designing an engine covering, or nacelle, for the airplane's motors that could do the job without affecting the X-57's overall aerodynamics. The nacelle was successfully tested by powering up an X-57 motor inside a wind tunnel.

Systems that would someday support deploying electric propulsion in larger airliners also were investigated during FY 2019. The first megawatt-scale test of an aircraft powertrain concept took place at NASA's Electric Aircraft Testbed, a repurposed hypersonic wind tunnel at NASA's Plum Brook Station in Sandusky, Ohio.

More information is available at the following locations:

- *https://www.nasa.gov/image-feature/nasa-glenn-keeps-x-57-cool*
- *https://www.nasa.gov/image-feature/neat-tests-megawatt-scale-electric-aircraft-power-systems*
- *https://www.nasa.gov/subject/7564/green-aviation/*

Highlights from NASA ARMD's Programs

Advanced Air Vehicles Program

NASA Aeronautics researchers from the Revolutionary Vertical Lift Technology project contributed to refining the design and operation of the Mars Helicopter scheduled to hitch a ride as part of the Mars Rover 2020 mission to the Red Planet. Researchers used some of their computational tools to characterize and better understand how well the small drone would fly in the Martian atmosphere. More information is available at *https://www.nasa.gov/feature/nasa-is-with-you-when-you-fly-even-on-mars*.

NASA wrapped up an effort that used 3D printing as a research tool to generate new data that will help airplane makers and operators more efficiently deal with icing. Those data, which will be publicly available in 2020, are the result of a cooperative five-year research program that involved NASA, the FAA , the French Aerospace Lab, and several U.S. universities. More information is available at *https://www.nasa.gov/aero/nasa-looks-to-3D-printing-to-improve-aircraft-icing-research-tools* and *https://www.nasa.gov/aam*.

Airspace Operations and Safety Program

With the conclusion of FY 2019, NASA logged the second successful year of a three-year exercise known Airspace Technology Demonstration–2. The research focuses on the schedule coordination of the movement of aircraft from an airport gate to the sky after takeoff, where they can safely join the overhead traffic—like a car merging onto a freeway. The big idea is to more reliably predict and schedule the time when aircraft are pushed back from their gates so that they can get to the runway and take off without pausing to wait in line on the runway while burning fuel and passengers' patience. Tangible benefits at the demonstration site in Charlotte, North Carolina, have already been realized, including saving the airlines 562,747 gallons of fuel and reducing CO_2 emissions equivalent to 86,481 urban trees (as of November 30, 2019).

During FY 2019, the NASA-developed technology behind the Automatic Ground Collision Avoidance System won aviation's highest award, the Collier Trophy, for its life-saving impact on flight. The system takes control of an aircraft upon determining that a collision with the ground is imminent. First the pilot is warned, but if no action is taken, the system locks the cockpit controls and performs an automatic recovery maneuver. More information is available at *https://www.nasa.gov/centers/armstrong/features/NASA-Celebrates-2018-Collier-Trophy.html*.

Integrated Aviation Systems Program

The X-59 QueSST airplane is designed to quiet a sonic boom heard on the ground to a sonic thump, if it can be heard at all. Accomplishing this goal requires the cockpit to be farther back and lower in the fuselage. This unusual design prevents the pilot from having a forward-facing window. To solve this problem,

NASA designed and successfully tested an eXternal Vision System (XVS) using a Beechcraft UC-12B research aircraft. The XVS relies on cameras and custom image-processing software to generate an augmented-reality view on a high-definition monitor mounted directly in front of the pilot. More information is available at *https://www.nasa.gov/feature/langley/testing-of-x-59-virtual-forward-window-successful*.

Testing of the wing that will be integrated into the final configuration of the X-57 Maxwell all-electric aircraft was completed during FY 2019. This high-aspect-ratio wing—longer and skinnier than conventional wings—will eventually hold a larger electric motor at each wingtip and 14 smaller electric motors evenly distributed across the wing's upper surface. Each motor will turn a propeller. NASA's first all-electric X-plane is intended to demonstrate the benefits electric propulsion may have for efficiency, noise, and emissions. More information is available at *https://www.nasa.gov/centers/armstrong/features/X-57-wing-tests-complete.html*.

NASA signed contracts with three industry partners in a bid to demonstrate progress in the use and eventual certification of Detect and Avoid and Command and Control systems critical to the safe operation of Unmanned Aircraft Systems in the National Airspace System. The demonstration is known as the Systems Integration and Operationalization activity and will take the form of a number of flight tests during the summer of 2020 using larger, various-sized, unpiloted aircraft built by each of the three companies. More information is available at *https://www.nasa.gov/aero/nasa-contracts-to-demonstrate-unmanned-aircraft-technologies*.

Transformative Aeronautics Concepts Program

Three teams of student researchers representing colleges in Pennsylvania, Wisconsin, and Illinois were selected during FY 2019 for participation in NASA Aeronautics' University Leadership Initiative (ULI). Their research topics include exploring new ways to use 3D printing and robotics in manufacturing, as well as investigating using liquid hydrogen–based fuel cells to generate power for electric aircraft propulsion systems. A key goal of ULI is for students to gain experience in leading a multi-disciplinary team made up of partners from other universities and industry, especially representing those who have not traditionally applied their skills to aviation problems. More information is available online at *https://www.nasa.gov/aero/nasa-aeronautics-selects-three-university-teams-for-research-help/*.

Space Technology Mission Directorate

The Space Technology Mission Directorate (STMD) develops transformative space technologies to enable NASA's future missions like Artemis. Technology drives exploration of the Moon, Mars, and beyond. Space Technology investments in revolutionary, American-made technologies provide solutions on Earth and in space. STMD engages and inspires entrepreneurs, researchers, and innovators across the country to advance American leadership in space. NASA technology turns up in nearly every corner of modern life. We make our space technology available to commercial companies to generate real-world benefits—everything from creating jobs to saving lives.

In FY 2019, STMD made significant progress toward advancing NASA's Artemis and deep space missions. In order to enable and enhance the Agency's capabilities, investments focused primarily in the following strategic areas:

- Go: Rapid, safe, and efficient space transportation, emphasizing reusable transportation from Earth to the Moon and/or Mars; and development of rapid and efficient transportation to explore throughout the solar system.
- Land: Expanded access to diverse surface destinations, routinely landing crew and cargo on the Moon and/or Mars; safely and efficiently returning large payloads to Earth; and delivering robotic payloads to challenging new destinations.
- Live: Sustainable living and working farther from Earth, routinely conducting crewed operations beyond low-Earth orbit; working toward a sustainable human presence on the Moon and/or Mars; and including production of propellant and consumables from local resources.
- Explore: Transformative missions and discoveries to reach challenging sites and resources on the Moon, Mars, and beyond; surviving and operating through the lunar night; and enabling rapid, low-cost missions to the Moon, Mars, and beyond.

As of FY 2019, STMD had over 1,000 active projects with over 400 industry partners and over 100 academic institutions. In addition, STMD has partnered with 16 other Government agencies or departments as well as five international organizations. In FY 2019, STMD evaluated more than 3,500 proposals and funded

more than 700 new technology selections, amounting to over $430 million in award investments.

NASA's investments in space technology advanced capabilities for future exploration missions. New technology demonstrations, challenges, and partnerships helped solve complex challenges needed to land on, live on, and explore the Moon and Mars.

Public-Private Partnerships

STMD continued to expand the use of public-private partnerships, focusing on technologies and capabilities needed for a sustainable presence on the Moon by 2028, showcasing NASA's commitment to the Nation's growing commercial space industry today.

The Space Technology Announcement of Collaboration Opportunity (ACO) selections, announced on July 30, included 19 new partnerships to mature industry-developed space technologies. NASA Centers will partner with U.S. companies, which range from small businesses to large aerospace organizations, to provide expertise, facilities, hardware, and software at no cost.

On September 27, STMD announced its selection of 14 American companies as partners whose technologies will enable the Agency's Moon-to-Mars exploration approach. The selections are based on NASA's fourth competitive Tipping Point solicitation and have a combined total award value of about $43.2 million. This investment in the U.S. space industry, including small businesses across the country, will help bring the technologies to market and ready them for use by NASA.

Technology Demonstration

The Deep Space Atomic Clock (DSAC) launched in late June aboard the SpaceX Falcon Heavy as part of the U.S. Air Force's Space Test Program (STP)–2 mission. DSAC is flying and validating a miniaturized, ultra-precise, mercury-ion atomic clock that is orders of magnitude more stable than today's best spacecraft clocks, potentially changing the way we conduct deep space navigation. DSAC was successfully activated in August and is in the process of conducting a yearlong

navigation demonstration that will provide a technology to improve accuracy of navigation and allow for gravity science measurements.

The Green Propellant Infusion Mission spacecraft also launched as part of the Air Force STP-2 mission in June. It began its demonstration of a propulsion system using a significantly less toxic propellant than hydrazine that provides 40 percent higher performance by volume. After a successful on-orbit checkout phase in July, the project is continuing its testing of the "green" fuel and propulsion system by performing three lowering burns that place the spacecraft in a different orbit. Once proven, this technology could lower the cost of fueling spacecraft before launch and provide efficient propulsion solutions for small and large satellites.

The Low-Earth Orbit Flight Test of an Inflatable Decelerator project completed inflation and vibration testing of a 6-meter engineering design unit (EDU) in the summer of 2019. The EDU was returned to NASA's Langley Research Center in July and underwent mass, center-of-gravity, and moment-of-inertia measurements in both the stowed and deployed configurations.

The Evolvable Cryogenics project is focused on developing, integrating, and validating cryogenic fluid management technologies for future NASA mission needs. In August 2019, the team successfully completed their baseline test series with liquid hydrogen at the Plum Brook Station Test Facility using the Structural Heat Intercept, Insulation and Vibration Evaluation Rig (SHIIVER). SHIIVER is a cryogenic tank for testing technologies and methods (such as vapor cooling and multilayer insulation) for maintaining very cold liquid propellants to be used as fuel for deep space missions.

Small Spacecraft Technology Program

In FY 2019, the Small Spacecraft Technology program successfully concluded the Optical Communications and Sensor Demonstration (OCSD) mission. This mission demonstrated the first-ever high-speed laser communication from a CubeSat as well as performing the first semiautonomous coordinated propulsive maneuver between two CubeSats. Supplemental to the primary objectives of the mission, OCSD also demonstrated a proof of concept for CubeSat-to-CubeSat optical communications with the secondary payload on the Integrated Solar Array

and Reflectarray Antenna (ISARA) mission that had previously been used to help develop the reflectarray technology for Mars Cube One (MarCO).

The CubeSat Handling of Multisystem Precision Time Transfer (CHOMPTT) mission—selected as one of ten CubeSats for the 19th Educational Launch of NanoSatellites (ELaNa) mission—launched in December 2018 on RocketLab's Flight 4 from Mahia, New Zealand. CHOMPTT will use lasers to transfer time code data between a pulsed laser system located at NASA's Kennedy Space Center and the CHOMPTT spacecraft. The CHOMPTT technology demonstration offers a timing system with performance similar to that of GPS and could be used for navigation and satellite networking in deep space.

In August, the Small Spacecraft Technology program awarded a $13.7 million contract to Advanced Space of Boulder, Colorado, to develop and operate the Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) mission to a near-rectilinear halo orbit (NRHO)—the same lunar orbit targeted for Gateway. CAPSTONE's objectives are twofold: serve as a Gateway pathfinder mission to demonstrate how to enter into and operate in an NRHO and demonstrate software for autonomous navigation. CAPSTONE represents a rapid lunar flight demonstration and could launch as early as February 2021.

Flight Opportunities

In FY 2019, the Flight Opportunities program facilitated the commercial suborbital flight testing of 43 technology development payloads across four suborbital reusable launch vehicle flights, one vertical takeoff/vertical lander flight campaign, six high-altitude balloon flights, and one parabolic campaign. U.S. commercial vendors providing flight services in 2019 included Black Sky Aerospace, Blue Origin, Masten Space Systems, Near Space Corporation, Raven Aerostar, Virgin Galactic, World View, and Zero Gravity Corporation.

In early FY 2019, both Virgin Galactic and Blue Origin flew their first dedicated suborbital spaceflights for NASA technology demonstrations. These flights carried a series of space exploration and utilization technologies, including research that could aid future missions in how they interact with the lunar surface to mitigate the impact of dust on humans and equipment; separate gas and liquid for in situ

resource processing and on-orbit fuel transfer; and understand plant behavior to potentially grow food for sustained human activity beyond Earth. In February, Virgin Galactic demonstrated four additional payloads, flying for the second time in just three months.

Raven Aerostar conducted a high-altitude balloon flight above Sioux Falls, South Dakota, in August 2019. The flight tested the Exo-Atmospheric Aerobrake technology from NASA's Ames Research Center and marked the first flight for Raven as a commercial flight provider for Flight Opportunities.

Game-Changing Development

The Astrobee project developed a free-flying robot system that includes three robots and a docking station for recharging and will be used to test how robots can assist crew and perform caretaking duties on spacecraft. Working autonomously or via remote control by astronauts, flight controllers, or researchers on the ground, the robots are designed to complete tasks such as taking inventory, documenting experiments conducted by astronauts with their built-in cameras, or working together to move cargo throughout the station. Robots like Astrobee will play a significant part in the Agency's mission to return to the Moon under the Artemis program, as well as in other deep space missions, by increasing astronaut productivity and helping maintain spacecraft when astronauts are not aboard. The Astrobee free flyers, Bumble and Honey, launched on the Northrop Grumman CRS-11 flight in April, and the third free-flying robot, named Queen, was launched to the space station in July aboard SpaceX's 18th commercial resupply services mission. Bumble underwent initial hardware checkout and mapping exercises; in June, it became the first to fly autonomously in space. Honey was "awoken" on its dock in November and will undergo additional testing before flying; Queen will be the last of the three to wake up in space.

The Safe and Precise Landing—Integrated Capabilities Evolution (SPLICE) project is developing an advanced suite of sensors, avionics, and software to avoid hazards and perform extremely safe, precise landings on the Moon. Engineers successfully demonstrated the performance of the terrain relative navigation (TRN) system being developed by Draper of Cambridge, Massachusetts, for use with

SPLICE. The test was held in Mojave, California, during the launch and landing of Masten Systems' Xodiac rocket on September 11. The TRN system uses a camera plus an onboard reconnaissance map to do image matching and feature tracking to navigate and to help target a desired landing region. The object of the testing was to use an existing map from orbital imagery to help provide precise navigation to target a desired landing region. The initial post-flight analysis shows that TRN successfully identified features in real time, and the test achieved all payload objectives.

The Mars Entry, Descent and Landing Instrumentation 2 (MEDLI2) project will collect data during the Mars 2020 mission's entry through the planet's atmosphere to enable improved designs of future Mars entry systems for robotic and crewed missions. Close analysis of MEDLI2 flight data is vital to future NASA exploration of the Red Planet. MEDLI2 delivered its flight hardware to NASA's Jet Propulsion Laboratory and was integrated with the Mars 2020 rover, along with STMD's other technology elements: TRN, the Mars Oxygen In-Situ Resource Utilization (ISRU) Experiment, and the Mars Environmental Dynamics Analyzer.

The Pop-Up Flat-Folding Explorer Robot (PUFFER) project demonstrated autonomous capabilities in June in an indoor testbed at NASA's Jet Propulsion Laboratory. During the test, PUFFER successfully navigated to locations predetermined by an operator while avoiding any rocks, accurately estimating its pose, and building a 2D map. During later tests, PUFFER successfully explored the testbed on its own without requiring a person to specify goals or a prior map.

The Space Synthetic Biology (SynBio) project is developing biomanufacturing methods that can produce high-value products on demand, using local resources. SynBio launched the first load of a five-year systems demonstration, called BioNutrients, to the ISS aboard NG-11 in April. The BioNutrients demonstration will test a newly developed in-space nutrient production platform that uses genetically engineered baker's yeast and an extended shelf-life growth substrate to produce specific antioxidants, such as beta carotene and zeaxanthin. SynBio is also developing a platform technology that chemically converts CO_2 and water to organic compounds that then "feed" microbial biomanufacturing systems to make a wide range of products such as food, medicines, and fuels.

Early Stage Innovation and Partnerships

Since its inception in FY 2011, Space Technology Research Grants has funded exciting space technology research via 696 grants at 111 universities across 43 states and one U.S. territory. In FY 2019, NASA made 14 Early Stage Innovations awards, nine Early Career Faculty awards, and 65 NASA Space Technology Research Fellowship awards. There are currently more than 300 active awards, including two new Space Technology Research Institutes, one led by Purdue University and one by the University of California, Davis, focused on deep space habitat autonomous operations to lay the technological groundwork that enhances and enables deep space exploration.

In FY 2019, NASA Innovative Advanced Concepts (NIAC) awarded 12 Phase I awards and six Phase II awards across industry, academia, and NASA Centers while completing 16 2018 Phase I studies and four 2017 Phase II studies. The remaining three 2017 Phase II studies are under no-cost extensions and on track to be completed in FY 2020.

In June, NIAC also awarded its first-ever Phase III selections, which outline aerospace architecture, including a mission concept that could change what is possible in space. Each selection will receive as much as $2 million to research and refine the proposed concept design and explore aspects of implementing the new technologies. The inaugural Phase III selections were as follows:

- "Robotic Technologies Enabling the Exploration of Lunar Pits" to rapidly survey and model lunar craters using high-resolution images to create 3D models of craters. The data would be used to determine whether a crater can be explored by human or robotic missions.
- "Mini Bee Prototype to Demonstrate the Apis Mission Architecture and Optical Mining Technology," which proposes a method of asteroid resource harvesting called optical mining. Optical mining is an approach for excavating an asteroid and extracting water and other volatiles into an inflatable bag.

NASA's Small Business Innovative Research (SBIR) and Small Business Technology Transfer (STTR) programs invested more than $180 million in small businesses in FY 2019. Specifically, 313 SBIR and 48 STTR Phase I proposals were

awarded to 268 U.S. small businesses to establish the scientific, technical, and commercial feasibility of each proposed innovation. This investment totaled more than $45 million.

The Centennial Challenges program concluded the third phase of its 3D-Printed Habitat Challenge in May 2019. The competition took place at a Caterpillar facility in Peoria, Illinois. The objective was to demonstrate technologies necessary to additively manufacture an off-world habitat. The final level of competition required teams to additively construct a 1:3 scale habitat autonomously. AI.Space Factory of New York took the first-place prize of $500,000, and a team from Pennsylvania State University took $200,000 for second place. The challenge awarded $2.06 million over the three phases of competition. In addition, the program continued to facilitate these other ongoing challenges:

- The purpose of the $1 million CO_2 Conversion Challenge is to convert carbon dioxide into sugars, such as glucose, as a step toward creating mission-critical resources. Such technologies will allow scientists to manufacture products on Mars using local, indigenous resources and on Earth by using waste and atmospheric carbon dioxide as a resource. Phase 1 of the challenge awarded $250,000 to five teams in May for their system concepts; phase 2 launched in September and seeks to award up to $750,000 to the top three teams that demonstrate operational systems in FY 2020.
- The purpose of the Vascular Tissue Challenge is to produce viable thick-tissue assays that can be used to advance research both on Earth and in space environments. This Challenge is ongoing, with 22 applications from 19 teams that submitted trial applications by the end of FY 2019. The teams are working on the development of vascularized, functional tissues for a liver, pancreas, heart, muscle, kidney, and/or lungs. The teams have one year to finish the development and prove that they can keep the tissue viable and functional for 30 days.
- The second phase of the Space Robotics Challenge opened in August and focuses on advancing robotics software and autonomous capabilities for space exploration missions on the surface of extraterrestrial objects, such as distant planets or moons. The $1 million competition will consist

of two rounds to narrow the field of competitors and will culminate with awards made in early FY 2022.

Technology Transfer

The Technology Transfer program continued to streamline and automate internal processes in order to increase the ability to conduct outreach to industry. The program continues to track, protect, and transfer technologies that play a part in going back to the Moon and tell the spinoff stories.

The NASA Home & City version 2.0 platform was launched in late FY 2018, and its use continued to expand through FY 2019. The interactive platform has been viewed by hundreds of thousands of users around the world. It also received nationwide recognition and awards, including top honors for the National Silver American Advertising Award. The interactive platform will also be displayed in museums all over the world and in other potential venues, such as airports and shopping malls.

The new NASA Software Catalog was released in November 2019. The digital and print catalogue serves as a complete inventory of software tools NASA has created during the course of mission work. The catalogue also serves as an avenue for industry, academia, other Government agencies, and the general public to download and use these software programs.

Department of Defense

DOD

Aeronautics

Rotorcraft

Army

Army Aviation continued to make strides in modernization and readiness while maintaining a global presence and ensuring world-class support to soldiers on the ground and our multinational partners. Army Aviation is currently 84 percent committed as it supports multiple deployments in support of U.S. Central Command, U.S. European Command, and U.S. Indo-Pacific Command. While supporting these deployments, aviation formations conducted home station training for their assigned Divisions and Brigade Combat Teams focused on large-scale combat operations, supported humanitarian assistance and disaster relief efforts, and trained for other contingencies.

The Army continued its modernization efforts across the entire aviation fleet. Rotary-wing aircraft fielding of the AH-64E Apache, HH/UH-60M Blackhawk, CH-47F Block II Chinook, HH-60V MEDEVAC Blackhawk, and LUH-72 Lakota ensured that Army aircraft will provide capability for decades to come. Unmanned Aircraft Systems (UAS) modernization includes improvements to the MQ-1C Gray Eagle and the RQ-7B Shadow, supporting enhanced crewed-uncrewed teaming. As the Army modernizes its current fleet of rotary-wing aircraft and UAS, it looks ahead with Future Vertical Lift (FVL) initiatives. The FVL Cross-Functional Team works closely with industry and is already integrating new technologies into the current force.

Program Executive Office (PEO) Aviation's Apache Helicopter Program Manager accepted the 300th AH-64E aircraft from the Boeing Company, and it will be assigned to the 82nd Combat Aviation Brigade (CAB), Fort Bragg, North Carolina—the 10th CAB to receive the AH-64E. In support of the continued fielding of the helicopter, a contract modification was awarded to Boeing fully funding Lot 9, which includes 48 AH-64E remanufactured aircraft and 12 AH-64E new-build aircraft. The Army Threat Systems Management Office conducted the AH-64E Version 6 Cyber Assessment marking the conclusion of Follow-On Test and Evaluation II. AH-64E Version 6 delivers quality and capability improvements to be fielded in the first quarter of FY 2021. The AH-64E is the current evolution of the Apache. It is designed and equipped with an open systems architecture, including the latest communications, navigation, sensor, and weapon systems. The E-model has multiple upgrades from its predecessors, such as the improved Modernized Target Acquisition Designation Sight/Pilot Night Vision System, which includes a new integrated infrared laser that allows for easier target designation and enhanced infrared imagery capabilities.

The Black Hawk UH/HH-60 is the Army's combat utility helicopter. This flexible system provides air assault, aeromedical evacuation, command and control, and general support to combat, stability, and multi-domain operations. PEO Aviation's Utility Helicopter Project Office continues to modernize the Black Hawk fleet with the UH-60V. The UH-60V updates legacy analog systems to a digital and open architecture. This architecture provides commonality with the UH-60M with a similar Pilot-Vehicle Interface. The UH-60V is now in the Low Rate Initial Production phase with an approved procurement of up to 76 UH-60V aircraft. The UH-60V completed Initial Operational Test and Evaluation Flight Testing at Joint Base Lewis-McChord, Washington.

The CH-47F Chinook is the Army's only heavy-lift cargo helicopter supporting combat and other critical operations. PEO Aviation's Cargo Helicopter Project Office delivered 12 aircraft to the 16th Combat Aviation Brigade, Fort Wainwright, Alaska, in FY 2019. Fielding will conclude in FY 2020 with the delivery of five CH-47F Block I aircraft to the 1st Battalion, 228th Aviation Regiment, in Honduras. As fielding of the Block I aircraft completes, development of the of the CH-47F Block II aircraft continues. Two of three test aircraft were delivered to

Mesa, Arizona, for system-level flight testing. The Block II upgrade provides additional capability with greater reach, increased payload capacity, and an increase in maximum gross weight.

PEO Aviation's Aviation Mission Systems and Architecture Project Office and the Aviation Ground Support Equipment Product Office successfully completed Aircraft Notebook (ACN) training and fielding to the U.S. Army Rotary Wing fleet. ACN replaced the Unit Level Logistics System–Aviation (Enhanced) system and set the conditions for introducing Global Combat Support System–Army Increment 2 Enterprise Aviation release 1 in FY 2020. ACN provides a common logistics information system for Army Aviation, streamlines user experience, improves record keeping, and provides the ability to view aircraft availability in near-real time across the fleet. To date, over 26,500 soldiers and civilians have been trained to use ACN and over 9,000 pieces of computer equipment have been converted. ACN fielding to the Fixed Wing fleet will begin in FY 2020.

Future Vertical Lift

The Future Vertical Lift (FVL) Cross-Functional Team (CFT), led by Brigadier General Walter "Wally" Rugen, is an Army-led, multi-service initiative, focused on enhancing vertical lift dominance through next-generation assets that provide increased reach, protection, lethality, agility, and mission flexibility. This initiative focuses on addressing aviation capability gaps against peer and near-peer competitors. The following four lines of effort address these gaps: Future Attack Reconnaissance Aircraft (FARA), Future Long Range Assault Aircraft (FLRAA), Future Tactical Unmanned Aerial Systems (FTUAS), Air Launched Effects (ALE), and the Modular Open System Architecture (MOSA). Four industry partners were selected for a FTUAS demonstration to take place in FY 2020 as the "Buy, Try, Inform" approach to inform user requirements. ALE demonstrations took place in Yakima Training Center in May 2019. Five industry partners will demonstrate their MOSA capabilities in a Capstone demonstration in December 2020.

The FARA Competitive Prototype (CP) negotiations were completed and five On Time As Promised (OTAP) awards were released in April 2019. The selection down to two vendors is scheduled for March 2020 to build the prototypes, with a

flight test scheduled for FY 2023. The FVL CFT released the FLRAA RFI to industry in April 2019, and the Joint Multi-Role Technology Demonstrator (JMR-TD) Technology Investment Agreement (TIA) was awarded in June/July 2019. The Vice Chief of Staff of the Army approved the Abbreviated Capability Development Document (CDD) in June 2019. This collaborative industry effort is developing an open system architecture for future platforms across the Department of Defense.

Navy

The U.S. Navy (USN) CH-53K Super Stallion program continued low-rate initial production with the award of Low-Rate Initial Production (LRIP) Lots 2 and 3 for 12 aircraft in June 2019. With nearly three times the external lift capacity of the CH-53E and a mission radius of up to 200 nautical miles, the CH-53K has the lift and range to support the future Marine Air Ground Task Force. Flight test operations continued throughout 2019 at Naval Air Station Patuxent River, Maryland.

The VH-92 Presidential Helicopter Replacement successfully completed Milestone C in May 2019, authorizing LRIP Lot 1 for the first six operational aircraft.

The V-22 Osprey has been in production for several years, with more than 380 aircraft delivered to the U.S. Marine Corps (USMC), Air Force, and United States Special Operations Command. This tiltrotor aircraft provides unique capabilities to the warfighter, combining the flexibility of a helicopter with the speed and range of a fixed-wing aircraft. In addition to the wide range of missions that the aircraft can currently support, new capabilities continue to be developed, such as the ability to act as a tanker for aerial refueling. Other upgrades are being completed to enable the aircraft to meet the USN requirements for carrier onboard delivery.

The Navy has delivered over 535 domestic MH-60 helicopters and transitioned all Helicopter Sea Combat and Helicopter Maritime Strike squadrons to the MH-60R/S. Due to high operational demand and evolving warfighter needs, the program has initiated a Service Life Assessment intended to evaluate requirements for a Service Life Extension. These efforts will improve mission systems/sensors, recapitalize current MH-60 investments to pace the threat, and establish the foundation to affordably migrate to the Future Vertical Lift platform.

In the fall of 2018, the United States commenced the effort to recapitalize its Advanced Helicopter Training System. The Navy is pursuing a nondevelopmental

approach and successfully completed Milestone/Full-Rate Production Review in October 2019.

Fixed-Wing

Navy

The transition of the P-3C to the P-8A continues to progress, with 88 P-8A aircraft delivered to the U.S. Navy and ten aircraft delivered to the Royal Australian Air Force under a cooperative agreement. The Navy has transitioned ten of 12 fleet squadrons.

The F-35 Joint Strike Fighter Program formally entered Initial Operational Test and Evaluation in December 2018 and made steady progress throughout FY 2019. The Navy's first F-35C squadron, Strike Fighter Squadron VFA-147, conducted aircraft carrier qualifications aboard the USS Carl Vinson in early December 2018 and received its safe-for-flight operations certification on December 12, 2018. Following this successful progress, the U.S. Navy declared Initial Operating Capability on February 28, 2019. The Marines continued their forward momentum, and in late January 2019, the 31st Marine Expeditionary Unit conducted the first flight operations with live ordinance in the Indo-Pacific region aboard the USS Wasp. In May 2019, the Navy deactivated VFA-101, to become part of VFA-125. Then, in order to consolidate all F-35C operations, the squadron relocated to Naval Air Station (NAS) Lemoore, California, from Eglin Air Force Base (AFB), Florida. In August 2019, the F-35 program achieved two more firsts: the first female U.S. Marine Corps F-35B pilot graduated from pilot training, and the first female Marine Officer was selected for the F-35C training pipeline.

Fifty-seven of 111 KC-130J aircraft have been delivered to the USMC, transitioning four active-duty squadrons and one reserve squadron. In addition, two C-40A aircraft were procured for the USMC Reserves.

The Navy and Air Force continue working on a joint Analysis of Alternatives to determine the best material solution to recapitalize E-6B and other National Command and Control Aircraft.

The U.S. Navy achieved a level of 80 percent of full mission capability for the F/A-18A-D Hornet, F/A-18E/F Super Hornet, and EA-18G Growler, meeting the

Secretary of Defense's requirement ahead of the end-of-FY-2019 deadline. In March 2019, the Navy awarded Boeing a $4 billion multi-year contract to build 78 F/A-18E/F Super Hornet fighter jets equipped with Block III enhancements and with service lives extended from 6,000 to 10,000 flight hours, further modernizing the Navy's strike fighter inventory.

The E-2D Advanced Hawkeye (AHE) Program has delivered 41 aircraft to date. The United States Navy awarded a multi-year procurement contract in April 2019 to build 24 E-2D AHE aircraft. A modification to that contract was made in September 2019 to add the procurement of nine Japan Foreign Military Sales E-2D AHE aircraft. A July 2019 Program of Record (POR) Requirements Review Board validated the requirement to procure a total of 86 E-2D AHE aircraft, up from the 75 aircraft validated by the prior POR. If the 2017 National Defense Authorization Act (NDAA) language is not rescinded, the POR should support nine carrier wings, or 92 aircraft to support ten carrier wings. Upgrades to the platform continue as the Navy plans to release Delta System/Software Configuration build 3 in the first quarter of FY 2020, allowing the E-2D AHE to outpace the evolving threat.

Unmanned Aircraft System

Army

The MQ-1C Gray Eagle Extended Range unpiloted aircraft system successfully completed a follow-on operational test and evaluation, the third major MQ-1C operational test. The test results indicated that the MQ-1C Gray Eagle Extended Range aircraft is operationally suitable with a combat availability of greater than 80 percent. The Gray Eagle full-rate production contract was awarded to procure 30 Gray Eagle Extended Range Aircraft, 30 Satellite Air Data Terminals, two Universal Ground Data Terminals, Government-furnished equipment repairs/maintenance, and associated program management. This contract completes the Gray Eagle Army acquisition objective of 204 aircraft. The MQ-1C provides the warfighter with dedicated, assured, multi-mission uncrewed aircraft system capabilities with the extended-range variation providing nearly 50 percent greater endurance. Additionally, in FY 2019, the Army began experimenting on a Future

Tactical Unmanned Aircraft Systems initiative that will eventually replace the RQ-7 Shadows in Brigade Combat teams. Currently, Shadows are assigned to all Brigade Combat Teams, Special Forces Groups, and Combat Aviation Brigades.

Navy

The MQ-4C Triton (formerly Broad Area Maritime Surveillance UAS) will develop maritime-capable UAS for operational deployment by providing persistent maritime Intelligence, Surveillance, and Reconnaissance (ISR) services. Along with the P-8A Poseidon, the Triton UAS is an integral part of the Maritime Patrol and Reconnaissance Force (MPRF) Family of Systems, and it will provide combat information to operational and tactical users such as the Expeditionary Strike Group (ESG), Carrier Strike Group (CSG), and Joint Forces Maritime Component Commander (JFMCC). Developmental testing on the baseline capability was completed in October 2017, and Early Operational Capability (EOC) was reached in 2018. The upgraded multiple intelligence (Multi-Int) capability is on track to support the maritime Intelligence, Surveillance, Reconnaissance, and Targeting (ISR&T) transition plan in FY 2021.

The MQ-8 Fire Scout UAS program provides real-time and non-real-time ISR data to tactical users without the use of crewed aircraft or reliance on limited joint theater or national assets. An MQ-8 system is composed of air vehicles (MQ-8B/MQ-8C), a Mission Control Station, Tactical Control System software, a Tactical Common Data Link, an Unmanned Aerial Vehicle (UAV) Common Automatic Recovery System for takeoffs and landings, payloads (electro-optical/infrared/laser designator rangefinder, Automated Information System [AIS], voice communications relay, radar, Mine Countermeasures, and other specialty payloads), and associated spares and support equipment. Fire Scout (MQ-8C) radar provides a 240-degree instantaneous field of view and a range of digital modes to include maritime surveillance, synthetic aperture, inverse synthetic aperture, weather detection, and ground moving target indicator. The MQ-8 launches and recovers vertically and can operate from all suitably equipped air capable ships (SEACS). Fire Scout is the first platform to successfully receive Cybersafe Certification. In addition, MQ-8 has completed Risk Management Framework certifications. MQ-8C achieved Initial Operational Capability (IOC) on June 28, 2019.

The MQ-25 program is rapidly developing an unpiloted capability to embark on CVNs (aircraft carriers with nuclear propulsion) as part of the Carrier Air Wing (CVW) to conduct aerial refueling as a primary mission and provide ISR capability as a secondary mission. MQ-25 extends CVW mission effectiveness range, partially mitigates the current Carrier Strike Group organic ISR shortfall, and fills the future CVW-tanker gap, mitigating Strike Fighter shortfall and preserving F/A-18E/F fatigue life. MQ-25 will achieve this through the use of a carrier-suitable, semiautonomous (human-in-the-loop, air vehicle executes preplanned missions) UAS (provided by the Air System segment) controlled through existing command, control, communications, computers, and intelligence networks from the control systems integrated into the CVNs. MQ-25 will initially be integrated aboard Nimitz-class aircraft carriers, followed by Ford-class. The Chief of Naval Operations and the Assistant Secretary of the Navy for Research, Development, and Acquisition have approved accelerated, streamlined processes for the program office to move the IOC from FY 2028 to FY 2024. The Government demonstrated this acceleration through the conduct of source selection culminating with the August 2018 contract award ($805 million) to Boeing. The combined Government-industry team will use modern processes and advanced technology, such as Model Based Systems Engineering and embedded teaming, to keep the program on track to be the fastest contract award-to-IOC of any modern major aviation program. MQ-25 performed its first successful test flights in the fourth quarter of FY 2019.

The RQ-21A Blackjack provides runway-independent persistent maritime and land-based tactical Reconnaissance, Surveillance, and Target Acquisition (RSTA) data collection, dissemination, and communications relay capabilities to the warfighter. The RQ-21A carries an electro-optical/infrared payload with a laser rangefinder and infrared pointer. For the United States Marine Corps, the RQ-21A Blackjack provides Marine Expeditionary Force (MEF) and subordinate commands with a dedicated ISR system capable of operating from both L-class ships and remote austere locations ashore, delivering intelligence products directly to the tactical commander in real time. For the Navy, the RQ-21A provides persistent RSTA support for tactical maneuver decisions and unit-level force defense/force protection for Navy ships, Marine Corps forces ashore, and Navy Special Warfare

(NSW) Units. IOC was declared by the Marine Corps in the second quarter of FY 2016 and by Naval Special Warfare in the fourth quarter of FY 2018. USMC and NSW production deliveries are complete, and the system now has over 11,300 operational flight hours.

Weapons

Army

The Army is actively pursuing advanced precision munitions with longer ranges to allow our aircraft to operate outside of threat weapon system effective ranges. These precision munitions will make U.S. aircraft more survivable in a peer/near-peer threat environment and help solve the anti-access, area-denial challenge posed by current threats while operating in an enemy integrated air defense system environment. Army Aviation is also developing smaller, more versatile modular missile technology that allows for a more scalable and tailorable precision munition for soft/mid-range targets. Tailoring of the munitions will allow a more affordable precision munition for our UAS. These smaller precision weapons will increase lethality and provide more flexibility in targeting.

The Army began fielding and improving other munitions, including the Joint Air-to-Ground Missile (JAGM) and the Advanced Precision Kill Weapon System (APKWS). The JAGM is a multi-mode guidance munition capable of Precision Point and Fire-and-Forget targeting. The multiple sensor design provides a capability that enables employment in adverse weather and against countermeasures while also affording simultaneous engagements on both moving and stationary targets with increased lethality. In 2019, the Army had multiple successful engagements with the APKWS in operational theaters, validating the capability and investments in lighter precision munitions.

Navy

During FY 2019, the Department of the Navy continued to mature its long-range Cruise Missile Strategy. Key developmental and sustainment tenets of this strategy include the demilitarization of Tomahawk Land Attack/Block III, support of the Tactical Tomahawk (TACTOM)/Block IV recertification program,

and the development/fielding of new Block V capabilities through the integration of modernization and obsolescence upgrades to TACTOM during a midlife recertification program (which extends the missile service life an additional 15 years), the fielding of the Long-Range Anti-Ship Missile (LRASM) as the Offensive Anti-Surface Warfare/Increment 1 material solution to meet near- to mid-term anti-access Anti-Surface Warfare (ASuW) threats, and the development of follow-on Next Generation Strike Capability (NGSC) weapons to address future threats and targets in time to replace or update legacy weapons while bringing next-generation technologies into the Navy's standoff conventional strike capabilities. NGSC includes capabilities to counter long-term anti-surface warfare threats and a surface- and subsurface-launched Next Generation Land Attack Weapon (NGLAW) to initially complement, and then replace, legacy land attack cruise missile weapon systems.

TACTOM was originally planned to end production after FY 2018 (Full Rate Production [FRP] 15), but the NGLAW Analysis of Alternatives (AoA) determined that Tomahawk, with its planned capabilities upgrades, is an effective long-range strike solution into the 2030s.

LRASM continues to pioneer advanced semi-autonomous strike weapon capabilities. In FY 2019, LRASM again had multiple successes, including a two-weapon salvo that demonstrated autonomous behaviors against multiple moving ships. Weapons were employed for the first time from an F/A-18 Super Hornet. The LRASM program also delivered the first tactical rounds to support F/A-18 Early Operational Capability.

Using multi-mode seeker and two-way datalink capabilities, the Joint Small Diameter Bomb II (SDB II) program provides an adverse-weather, day-or-night standoff capability against mobile, moving, and fixed targets and enables target prosecution while minimizing collateral damage. During FY 2019, SDB II completed USAF operational test flights on the F-15E. The operational test report and fielding for the USAF is expected in early 2020. The Department of the Navy (DON) began developmental test flights in 2019 on both the F/A-18E/F and the F-35. The Navy is on track to field SDB II on the F/A-18E/F in the fourth quarter of FY 2020 and on the F-35B in 2021 for the USMC. DON procured 750 weapons (Lot 5) in 2019 with deliveries in 2021.

The APKWS guidance kit transforms an unguided 2.75-inch (70-millimeter) rocket into a precision-guided rocket, giving warfighters a low-cost surgical strike capability. The APKWS rocket redefines precision by hitting the target with pinpoint accuracy and minimal collateral damage. The rocket has been proven in combat for five years. The APKWS II continued its high level of reliability and lethality as this weapon has become one of the key weapons in the current fight against the Islamic State (known variously as ISIS and ISIL). The Navy has delivered 29,636 APKWS guidance kits to date to Navy/Marine, Air Force, Army, and Foreign Military Sales customers. Efforts are under way to develop a Single Variant guidance kit to replace separate Rotary Wing and Fixed Wing versions; increase fleet logistical flexibility; and address component part obsolescence.

Aviation Survivability Equipment

Army

Aviation Survivability Equipment (ASE) is essential to providing force protection for aircraft against emerging advanced threats. Nowhere is this more evident than in the Concept of Operations (CONOPS) for FVL in Multi-Domain Operations (MDO). Therefore, while we continue to maintain capable ASE systems in the current fleet and develop advanced capabilities to counter an ever-evolving array of threat systems, we are viewing the future of ASE through an FVL lens. In 2019, the Army continued a concerted effort to modernize the infrastructure for its Aircraft Survivability Equipment in order to allow for more rapid and responsive fielding of improved threat detection and defensive countermeasures. The Common Missile Warning System (CMWS) continues to provide the Army's fleet with infrared (IR) threat detection with the primary focus on Man Portable Air Defense Systems (MANPADS). CMWS employs a range of expendable countermeasures on all platforms with the addition of the Advanced Threat IR Countermeasure system on CH-47s to defeat incoming MANPADS. Army Aviation has begun receiving production systems of the Common Infrared Countermeasure and the initial component deliveries of the Limited Interim Missile Warning System (LIMWS), a directed requirement increment intended as a rapid capability insertion for improved protection of Army helicopters. Army

Aviation is also developing requirements for the next-generation ASE systems with an eye toward both FVL and the current fleet. Those advanced capabilities have to protect U.S. aircraft and crews against a range of advanced MANPADS as well as vehicle-borne systems that include radar, laser, and various passively cued systems. FVL efforts provide the ASE program office with a unique opportunity to assess the offerings from FVL competitors, in addition to ongoing developmental programs.

In the area of Radio Frequency (RF) systems, the Army is doing a validation installation of the APR-39D(V)2 Radar Warning Receiver to begin its fielding. APR-39D(V)2 is a bridging capability to be used while the Army continues the development of the APR-39E(V)2, Modernized Radar Warning Receiver. Along with advances in detection capabilities, the Army is advancing its threat defeat capabilities by developing a family of Advanced Airborne Expendable Countermeasures and is pursuing opportunities to accelerate active RF Countermeasures capabilities. Production of an improved counter-RF expendable (Chaff) is expected to field to the force in 2024. The fielding of upgraded Chaff and Electronic Countermeasures will coincide with the improved detection initiatives, with an eye toward implementation in FVL platforms as well as the current fleet. MDO requirements will continue to drive Army Aviation science and technology efforts to develop follow-on systems that are able to detect and defeat a threat system regardless of its targeting and guidance systems, propulsion means, or warhead type.

Propulsion

Army

The Army is developing the Improved Turbine Engine (ITE), a 3,000-shaft-horsepower engine, designed to replace the current GE 701D engine that powers the AH-64 and UH-60 airframes. The PEO Aviation/Aviation Turbine Engines Project Office successfully executed the ITE Program Milestone B for the Acquisition Oversight Integrated Process Team and Army System Acquisition Review Council. The Army Acquisition Executive approved the ITE Acquisition Program Baseline, establishing parameters for the engineering, manufacturing, and development phases. Contracts were awarded to integrate the ITE into the Apache and Black Hawk platforms. The ITE will restore capabilities lost due to consistent airframe

growth over the last 40 years and provide significant fuel savings, significant power enhancement, and worldwide performance to meet operational requirements. Its modular design will simplify and enable field-level repair and lower operation and sustainment costs.

Space

Environmental Monitoring

Air Force

The Weather System Follow-on (WSF) is a two-phased acquisition approach that places the Compact Ocean Wind Vector Radiometer (COWVR) technology demonstration in 2021 on the International Space Station (ISS). The COWVR demonstration is intended to mature the technology and develop ground-processing algorithms. The WSF-Microwave (WSF-M) program will collect critical observations on Ocean Surface Vector Winds and Tropical Cyclone Intensity. WSF-M is the planned replacement for the legacy Windsat mission as well as the Special Sensor Microwave Imager/Sounder (SSMIS) sensors that fly on the Defense Meteorological Satellite Program (DMSP) satellites. The first of up to two WSF-M satellites is in development, with acquisition Milestone B planned for late 2019 and initial launch capability in late 2023.

The Electro-optical/infrared Weather System (EWS) (formerly WSF-E) pre-acquisition activities were conducted throughout the year, leading to an approved acquisition strategy in summer 2019. EWS will satisfy DOD's two highest-priority Space Based Environmental Monitoring (SBEM) sensing needs from the family of systems' "early-morning" orbit—Cloud Characterization and Theater Weather Imagery.

Throughout 2018, the Air Force and NOAA conducted various technical interchanges, site surveys, and planning activities for EWS-Geostationary (EWS-G, formerly WSF-G). The intended purpose of EWS-G is to provide persistent weather monitoring of the Central Command (CENTCOM) Area of Responsibility (AoR) from a dedicated U.S. geostationary SBEM satellite. GOES-13 will become the repurposed and redesignated EWS-G. This coverage is currently provided by the

allied European Meteosat-8 which has a projected end of mission in 2020. EWS-G will ensure that U.S. operations in the CENTCOM continue to be supported by timely and reliable SBEM capabilities when the current Meteosat-8 support ends. Work continues to establish a remote ground station in western Australia that will be operational by late 2019.

The Space Situational Awareness Environmental Monitoring (SSAEM) program is a technology demonstration project to support the international Constellation Observing System for Meteorology, Ionosphere, and Climate 2 (COSMIC-2) mission. The SSAEM program provides the acquisition, development and launch/on-orbit support of 18 space/terrestrial weather sensors as well as COSMIC-2 partnership in coordination with NOAA and Taiwan's National Space Organization (NSPO). COSMIC-2 launched six satellites in an equatorial, low-Earth orbit (LEO) with three SSAEM sensors in each spacecraft in June 2019. The sensor types are Tri-Global Navigation Satellite System (Tri-GNSS) Radio occultation System (TGRS), Ion Velocity Meter (IVM), and Radio Frequency Beacon (RFB). The SSAEM sensors observe ionospheric density, equatorial ionospheric scintillation, and electric field to provide additional space meteorological data that should improve forecast capabilities and warfighter navigation/communication capabilities over the next five years.

Missile Warning/Attack Assessment

Air Force

The Space Based Infrared System (SBIRS) provides ballistic missile warning and defense, battlespace awareness, and technical intelligence for the United States and its allies. SBIRS satellites and ground systems currently provide operational capability and will continue to incrementally deliver additional capability to the future warfighter.

SBIRS Geosynchronous Earth Orbit (GEO) 4 (the third SBIRS GEO launch) is fully functional and entered operations in May 2019. The SBIRS GEO 5 and GEO 6 production contract was awarded on June 24, 2014, using a six-year Efficient Space Procurement (ESP) that provided a cost avoidance of $521 million. The SBIRS GEO 5 and GEO 6 satellites are in production and are meeting cost and

schedule objectives. The SBIRS GEO 5 primary mission payload completed physical integration with the Space Vehicle in July 2019 and is ready to begin Space Vehicle integration and test activities.

SBIRS Ground, Block 20 (Software Baseline Review 18-1), was operationally accepted on August 29, 2019, delivering mission-processing enhancements, improved detection/accuracy, and automated tasking.

The Air Force is taking projected threats seriously and focusing investments on maturing resilient technology. An acquisition strategy was approved for the Next Generation Overhead Persistent Infrared (Next-Gen OPIR) space segment, and an acquisition strategy for the Next-Gen OPIR ground segment is in pre-decisional forums within the Air Force. The space segment will replenish the SBIRS constellation by delivering five resilient and survivable Missile Warning Satellites (three GEO and two Polar Orbit).

The Ground Segment, Future Operationally Resilient Ground Evolution (FORGE), is developing a cyber-secure open OPIR mission framework capable of hosting applications and providing services to process mission data for missile warning, missile defense, battlespace awareness, and technical intelligence mission areas. This year, FORGE conducted an initial prototyping effort to develop the mission data application framework that will result in an FY 2020 downselect to a single provider.

Positioning, Navigation, and Timing

Air Force

The Global Positioning System (GPS) program celebrated its 24th anniversary this year of providing uninterrupted Positioning, Navigation, and Timing (PNT) data, free of charge, to users worldwide. GPS has been operational since July 1995. The success of the GPS program can be reflected in the total number of GPS receivers produced to date, estimated at more than four billion worldwide. The first two GPS III satellite launches occurred in December 2018 and August 2019, ushering in the next generation of GPS technology with significant enhancements to the current constellation, including higher-power military signals, new civilian signals, and hosted search-and-rescue payloads.

The GPS III Follow-on (GPS IIIF) contract is under way and currently in the design and development phase. GPS IIIF satellites will provide an eightfold increase in anti-jam performance over current GPS satellites.

The GPS next-generation Operational Control System (OCX) is a modernized ground system that will enable the effective use of the latest military and civilian GPS signals while providing significantly improved cyber resiliency. OCX Block 0 successfully performed the launch and on-orbit checkout of the first two GPS III satellites. The OCX Block 1/2 development phase was completed in August 2019, signaling the transition of the program into integration, test, deployment, and eventually operation.

The Military GPS User Equipment (MGUE) first ground systems card completed Technical Requirements Verification in March 2019, signifying that it is ready for integration into Department of Defense platforms. These Military GPS receiver cards provide users with access to higher-power military signals and are more jam-resistant than previous generations.

Satellite Communications (SATCOM)

Air Force

The Advanced Extremely High Frequency (AEHF) system is a joint-service satellite communications system that provides global, survivable, secure, protected, and jam-resistant communications for high-priority military ground, sea, and air assets. Four on-orbit AEHF satellites augment the existing Milstar constellation, providing protected satellite communications for strategic users. A fifth satellite was successfully launched on August 8, 2019.

The Evolved Strategic SATCOM (ESS) program is the disaggregated strategic communications follow-on to the AEHF program. The Air Force will employ competitive rapid prototyping on the ESS space segment with up to three potential contractors—Northrop Grumman Corporation, Lockheed Martin Space Systems Company, and the Boeing Company—simultaneously via sole-source contracts. The rapid prototyping request for proposals was released on August 29, 2019.

The Protected Tactical SATCOM (PTS) program is the disaggregated tactical communications follow-on to the AEHF program. PTS will provide worldwide,

beyond-line-of-sight, anti-jam, low-probability-of-intercept communications to tactical warfighters in both benign and contested environments. PTS was designated as an MTA, Rapid Prototyping Activity in November 2018, and it will develop two prototype payloads available for launch three years earlier than a traditional DOD 5000.02 acquisition. The rapid prototyping request for proposals was released on May 23, 2019.

The Family of Advanced Beyond-Line-of-Sight Terminals (FAB-T) program will field nuclear-event-survivable terminals capable of communicating with the Milstar and AEHF satellite constellations using jam-resistant, low-probability-of-intercept, and low-probability-of-detection waveforms. On February 7, 2019, the Milestone Decision Authority approved the procurement of all FAB-T Command Post Terminals (CPTs) during Low Rate Initial Production. All 84 planned terminals are now on contract; 27 terminals have been delivered; 12 terminals have been installed; and eight are in operational use.

The Protected Tactical Enterprise Service (PTES) is a ground system that will provide an anti-jam protection via Wideband Global SATCOM (WGS) to tactical warfighters currently unable to operate through interference in anti-access/area-denial operational environments. On June 18, 2018, the Senior Acquisition Executive designated PTES as an FY 2016 NDAA, Section 804, Middle Tier of Acquisition, Rapid Prototyping activity and authorized PTES to pursue a prototype capability (communications supporting two Navy Carrier Strike Groups in the Pacific Theater) in early FY 2022. Boeing was awarded the PTES development contract in November 2018. The Hardware System Requirements Review was held in March 2019, and the Software Build Decision Review #1 was accomplished in August 2019.

The Enhanced Polar System (EPS) program, with two hosted payloads on orbit and a ground Control and Planning Segment (CAPS), received Initial and Final Operational Capability (IOC/FOC) declaration on September 19, 2019. EPS replaces the Interim Polar System to ensure that critical protected communications requirements above 65 degrees north latitude are satisfied for joint forces. The Air Force is procuring two replenishment EPS payloads to prevent a MILSATCOM mission gap in the Polar Region in the 2025 timeframe. These EPS-Recapitalization (EPS-R) payloads will be hosted on satellites procured by Space Norway because it

promotes U.S. policy to strengthen international partnerships and has the potential for the U.S. Government to avoid $900 million of costs. The agreement was codified in a Memorandum of Agreement in May 2019. A successful EPS-R payload Preliminary Design Review was accomplished in November 2018. An update to the EPS CAPS was awarded to Northrop Grumman Mission Systems (NGMS) in May 2019.

The WGS satellite program consists of 11 satellites with ten currently on orbit. WGS 10 successfully launched on March 15, 2019. The Consolidated Appropriations Act, FY 2018, includes an allocation of $600 million for two additional WGS satellites. The decision was made that a single WGS-11+ satellite with twice the operational capacity of WGS-10 would be procured. Boeing delivered a proposal in January 2019, and the Space and Missile Systems Center (SMC) issued an Undefinitized Contract Action for WGS-11+ (with twice the capacity of WGS-10) on April 19, 2019. WGS is the DOD SATCOM constellation with the highest capacity and was declared at Full Operational Capability (FOC) with five satellites on May 12, 2014. The WGS system provides high-data-rate two-way X-band and Ka-band communications to support various missions of the Unified Combatant Commanders, military services, other DOD agencies, and international partners (Australia, Canada, Denmark, Luxembourg, the Netherlands, New Zealand, Norway, and Czech Republic). The WGS system is composed of space, control, and terminal segments. The space segment operates in the X-band and Ka-band with flexible connectivity between bands and coverages to support and connect users operating worldwide.

The Air Force Commercial SATCOM Office (AFCSCO) was established under Air Force Space Command (AFSPC) in December 2018. AFCSCO procures Commercial SATCOM (COMSATCOM) for DOD by managing over 90 active customer contracts and leveraging 40 commercial SATCOM providers. AFCSCO delivers access to the global commercial Iridium Satellite Constellation for DOD, all federal agencies, state and local governments, and foreign partners (Five Eyes [FVEY] and the North Atlantic Treaty Organization [NATO]). AFCSCO also delivers COMSATCOM capabilities through standard and custom contracts, including transponder capacity, managed services, and custom solutions.

Space Access

Air Force

The Evolved Expendable Launch Vehicle (EELV) program was renamed National Security Space Launch (NSSL) on March 1, 2019, per the FY 2019 National Defense Authorization Act. The program continues to successfully place satellites into orbit. United Launch Alliance (ULA) continued its record of success, with five National Security Space (NSS) launches as of September 20, 2019. Space Exploration Technologies (SpaceX) flew their first NSS launch, as well as their first Air Force Falcon Heavy Launch for the Space Test Program (STP). A summary of the seven launches during FY 2019 follows:

(Launch Date, Launch Vehicle Configuration, Payload)

- October 17, 2018, Atlas V (551), AEHF-4
- December 23, 2018, Falcon 9, GPS III-2
- January 19, 2019, Delta IV Heavy, National Reconnaissance Office Launch (NROL)–71
- March 16, 2019, Delta IV Medium+(5,4), WGS-2
- June 25, 2019, Falcon Heavy, STP-2 (non-NSS)
- August 8, 2019, Atlas V(551), AEHF-5
- August 22, 2019, Delta IV Medium+(4.2), GPS III-1

On October 10, 2018, the Air Force awarded Launch Service Agreements (LSAs) to Blue Origin, Northrop Grumman, and ULA to develop launch systems prototypes. These LSAs were a key step in the transition from the use of non-allied space launch engines to domestically produced engines. This enables assured access to space and introduces sustainable competition for future National Security Space launch services.

The Air Force, in partnership with the National Reconnaissance Office (NRO), competitively awarded firm-fixed-price launch services contracts to SpaceX and ULA under the EELV/NSSL Phase 1A procurement strategy on February 19, 2019. Six missions were awarded, with AFSPC-44, NROL-85, and NROL-87 going to SpaceX and SBIRS GEO-5, SBIRS GEO-6, and SILENTBARKER going to ULA. The award includes launch vehicle production, mission integration, and launch operations. This is the sixth competition under the Phase 1A EELV/NSSL

procurement. These contract awards represent the Air Force's continued effort to strike a balance between meeting operational needs and lowering launch costs by reintroducing competition for National Security Space missions.

A Request for Proposals for the NSSL Phase 2 Launch Service Procurement (LSP) was released on May 3, 2019. The Air Force intends to competitively award Phase 2 LSP contracts to two launch service providers for launch service procurements between FYs 2020 and 2024, to be launched from 2022 through 2027.

On September 30, 2019, the Air Force awarded ULA a five-year $1.18 billion contract for launch operations to complete the last planned five Delta 4 Heavy National Reconnaissance Office (NRO) missions from 2020 through 2024. The award covers the launch operations costs for five classified NRO missions—NROL-44, NROL-82, NROL-91, NROL-68, and NROL-70. The Air Force already had acquired five Delta 4 Heavy rockets for these missions under previous contracts awarded to ULA in 2017 and 2018.

Range modernization efforts continued in FY 2019 with the following accomplishments:

- Architectural overhauls at the Eastern and Western Ranges with sustainment engineering and modification projects to address cybersecurity issues, obsolescent technology, and diminishing vendor concerns. Modernization of Range subsystems such as telemetry, radar, and command site instrumentation and associated software to ensure mission reliability, maintainability, and availability.
- Eastern and Western Range network modernization continued, with upgrades for mission communications core to provide automated routing versus manual Range reconfiguration; centralized network management across the IP network; increased bandwidth, enabling transport of Range data now and in the future; and opportunities to modernize information assurance.

The Air Force's Rocket Systems Launch Program (RSLP) continues to provide a low barrier for new entry launch vehicles, enabling a diverse vendor pool consisting of both large and small businesses with a mixture of mature and emerging launch providers. One example in FY 2019 is the Space Test Program–2 mission launched on the Air Force's first SpaceX Falcon Heavy launch vehicle, putting 23

experimental satellites into orbit on June 25, 2019. Additionally, RSLP seeks to capitalize on the dynamic small satellite market by employing a flexible launch program, showcasing industry's innovation while providing affordable launch solutions. This led to its partnership on the STP-27RD mission using the Rocket Lab Electron launch on May 5, 2019, and its recent award on the Small Rocket Program–Orbital contract to Aevum for a Ravnx launch scheduled for 2021.

In FY 2019, the Space Test Program (STP) successfully deployed two spacecraft from the International Space Station. The U.S. Army's Kestrel Eye is a prototype, low-cost, visible-imagery small satellite designed to provide near-real-time images to the tactical-level ground soldier. The payload was deployed into space and activated in October 2018. Additionally, STP launched and deployed the Defense Advanced Research Projects Agency's (DARPA) Red-Eye 1 spacecraft from the ISS. Red-Eye 1's objective is to develop and demonstrate technologies that increase the utility of low-cost microsatellites. The spacecraft was successfully deployed from the ISS.

In addition to spacecraft deployed from the ISS, the STP launched and successfully installed STP-H6 on the ISS's Express Logistics Carrier in May 2019. The STP-H6 carried seven DOD Space Experiments Review Board (SERB)–approved experiments to the ISS. STP-H6 is in its operational phase. In July 2019, the STP launched the U.S. Army's cell science experiment investigating new pharmaceuticals for the treatment of bone damage in wounded warriors. Cell samples were returned to Earth on SpaceX-18.

The Space Test Program continues to support NASA's Lightning Imaging Sensor (LIS), part of the experiment complement on the STP-H5 payload on the ISS. LIS operations have been extended on a reimbursable basis after STP's experiments on STP-H5 have concluded. LIS is supplying operational data to the National Weather Service for storm warnings, nowcasts, oceanic aviation, and international meteorological events. It has also been a benefit in military operations and will play an important role in the extension period for improving National Climate Assessment studies that benefit Government decision making regarding the complex impacts of climate change on U.S. infrastructure.

Finally, in September 2019, the STP turned over the STP-built STPSat-4 spacecraft and the U.S. Navy's LEctenna experiment to NASA for launch from the ISS. STPSat-4 will fly five Space Test Experiment Review Board experiments and

also demonstrate the operational utility of the Commercial Augmentation System (CAS) and is expected to deploy from the ISS in January 2020. STPSat-4 uses three CAS ground stations in the United States and OCONUS. LEctenna is a SERB-approved experiment and was the first ISS payload to use a commercial integration process. Integration was accomplished in 30 days. LEctenna will launch to the ISS in December 2019.

Space Rapid Capabilities Office (SpRCO)

In 2019, the NDAA further defined the SpRCO mission to contribute to the development of low-cost, rapid-reaction payloads and systems to rapidly develop and field new highly classified space capabilities in support of national defense. It also directed the Secretary of the Air Force to establish a Board of Directors (BoD). The BoD is chaired by the Secretary of the Air Force with membership that includes the Chief of Staff of the Air Force; Commander of the U.S. Space Command; Assistant Secretary of the Air Force for Acquisition, Technology, and Logistics; Undersecretary of Defense for Acquisition and Sustainment; and Undersecretary of Defense for Research and Engineering. Through the BoD, the SpRCO has been assigned and is executing programs that fill critical portions of the Space Warfighting CONOPS as defined by the Commander of the U.S. Space Command. The SpRCO is further developing partnerships with other Government organizations, industry, academia, and Federally Funded Research and Development Centers to aid in fulfilling its mission.

Space Control

Air Force

The Counter Communications System (CCS) provides expeditionary, deployable, and reversible counter-space effects applicable across the full spectrum of conflict. CCS denies adversary satellite communications in an area of conflict. CCS is a key piece of DOD's space control strategy and has been in operation since 2004 with the fielding of three Increment 10.0 systems. To date, CCS has gone through two subsequent preplanned product improvements and has delivered 14 of 16 CCS

Increment 10.2 systems, with the remaining systems to be delivered to operational units by the third quarter of FY 2020. In calendar year (CY) 2019, the Increment 10.3 upgrade began and will deliver four systems in FY 2022.

The Space Security and Defense Program (SSDP) is a joint DOD and Office of the Director of National Intelligence (ODNI) organization, established to function as the center of excellence for options and strategies (materiel and non-materiel), leading to a more resilient and enduring National Security Space Enterprise. In FY 2019, SSDP completed efforts resulting in the delivery and implementation of specific cyber and materiel solutions to emergent capability needs. These include the following:

- Developing and accessing protection capabilities, architectures, and requirements across the NSS enterprise.
- Performing technical analyses, studies, and modeling to inform national, DOD, and Intelligence Community (IC) policy for enhancing the U.S. space protection posture.
- Designing and developing tools that provide actionable recommendations to individual programs for increasing system resiliency and informing investment decisions.
- Maturing analytical capability to evaluate resiliency of proposed architectures (both mission-specific and enterprise-wide).
- Developing experiments and exercises to advance space protection Tactics, Techniques and Procedures (TTPs); Concept of Operations (CONOPS); and Space Situational Awareness (SSA) command and control (C2).
- Prototyping C2 and SSA integration solutions to speed information sharing, streamline operations, and shorten decision timelines.
- Refining Space C2 requirements based on National Space Defense Center experiment results, C2 prototypes, and SSA experiments.

Space Situational Awareness

Air Force

Adversary nations are fielding sophisticated space weapons at a pace that our legacy SSA and space C2 systems cannot currently match. To address the rapidly

expanding threats to the space enterprise, the Space Command and Control (C2) system will allow the Department of the Air Force to command and control space control and SSA forces by integrating data for commanders. The system will create decision-relevant views of the space environment; rapidly detect, track, and characterize objects of interest; identify and exploit traditional and nontraditional sources; perform space threat analysis; and enable the efficient distribution of data. It will be an integral tool to help commanders develop courses of action to address threats to critical space assets. The program's new acquisitions approach is an innovative agile DevSecOps effort, which links users with developers to deliver improved and prioritized capabilities to operators on a recurring basis. This pivots future SSA and C2 development efforts to a user-driven, rapid-delivery approach in order to defeat an advancing threat.

Space Fence provides un-cued surveillance of small objects and satellites primarily in Low-Earth Orbit (LEO), as well as Medium-Earth Orbit (MEO) and Geosynchronous Earth Orbit (GEO) (secondary), to provide spaceflight safety, early detection, custody of threats, and awareness to satellite operators in the human spaceflight regime. Space Fence will be the most accurate high-capacity radar in the Space Surveillance Network (SSN) and will provide extensive updates to the space catalogue; increase sensitivity for new object discovery; and deliver optimum orbital coverage, including coverage of much lower inclinations of orbiting objects. Space Fence greatly increases the ability to understand the Space Domain battlespace and inform warfighter decisions. The increased sensitivity, coupled with increased computing capabilities of the Joint Space Operations Center Mission System, improves understanding of the space operating environment and associated threats.

The acquisition strategy implements Better Buying Power—cost, capability, and design trade studies; prototyping; and risk reduction in the System Development and Preliminary Design Review phases. Current efforts are focused on the first site and the operations center, which provide system IOC. The program is currently conducting operational testing and is on track to achieve IOC in the first quarter of FY 2020.

Federal Aviation Administration

FAA

The Federal Aviation Administration (FAA) has achieved more milestones in its ongoing Next Generation Air Transportation System (NextGen) effort. NextGen is transitioning the National Airspace System (NAS) from analog and ground-based communication, navigation, and surveillance systems to cutting-edge digital and satellite-enabled technologies. NextGen is fundamentally changing the way we see, navigate, and communicate in the Nation's skies.

NextGen seeks to move away from the current system of air traffic control (ATC)—based on knowing where an aircraft is using radar—to a time-based management system that operates on shared knowledge of the precise location of an aircraft at any given point in time along its projected trajectory. Trajectory Based Operations (TBO) is an air traffic management (ATM) method for strategically planning, managing, and optimizing flights throughout the operation by using time-based management, information exchange between air and ground systems, and the aircraft's ability to fly precise paths in time and space. TBO will increase safety, reduce delays and congestion, decrease fuel burn, and lower aircraft exhaust emissions.

Automation

Two cutting-edge automation systems are helping to modernize ATC. While neither platform is a NextGen technology in and of itself, both enable critical NextGen capabilities in terminal and en route airspace.

Under the Terminal Automation Modernization and Replacement (TAMR) program, the FAA is replacing the Automated Radar Terminal System in terminal radar approach control (TRACON) facilities with the Standard Terminal Automation Replacement System (STARS). TRACONs guide aircraft transitioning to and from high-altitude airspace.

STARS is replacing the automation in TRACONs and their associated air traffic control towers across the country. They system is now operational at 99 percent of all TRACONs, including the 11 sites that control 80 percent of U.S. traffic:

- Atlanta
- Chicago
- Dallas/Fort Worth
- Denver
- Louisville
- Minneapolis/St. Paul
- New York
- Northern California
- Potomac (Washington, DC, area)
- St. Louis
- Southern California

STARS enables many NextGen technologies in terminal airspace, such as Automatic Dependent Surveillance–Broadcast (ADS-B), the satellite-based successor to radar, and the advanced terminal sequencing and spacing function for Time Based Flow Management (TBFM).

The FAA completed deploying the En Route Automation Modernization (ERAM) system to all 20 air route traffic control centers in the contiguous United States in 2015. Like STARS, ERAM enables key NextGen capabilities in the facilities that control traffic at cruising altitude, including the fully integrated ADS-B and Data Communications (Data Comm), which supplements voice communications with digital text-based messages between controllers and pilots. ERAM Enhancements 2 continues the incorporation of new capabilities, such as enhancing the accuracy of Aircraft Trajectory Modeling and Conflict Probe, as well as the expansion of the automated coordination of flight data and aircraft control with NAV Canada, the Canadian air navigation service provider.

Data Communications

Departure clearance tower service is active at 62 U.S. locations. The FAA finished the first 55 locations more than two years ahead of schedule in December 2016. The team then targeted seven additional sites using program underrun funds and completed those additional installations in August 2018—13 months ahead of the original 55-airport baseline.

Using Data Comm, controllers select and send departure clearance instructions electronically to the cockpits of equipped aircraft instead of speaking them to pilots over the radio. Air carrier flight operations centers simultaneously receive the same information, giving all decision makers a shared awareness for faster reactions to changes. Flight crews signal concurrence with the press of a button. Instructions can then be loaded into the aircraft's flight management system. By providing an air-to-ground data link, this transformational program is a critical component of the FAA's vision for TBO.

Data Comm is a priority focus area identified by the NextGen Advisory Committee (NAC). Composed of senior Federal and industry aviation stakeholders, the NAC provides independent advice and recommendations to the FAA and responds to specific taskings from the agency. The NAC also recommends consensus-driven standards relating to Air Traffic Management System modernization for FAA consideration.

The FAA is taking the next step for Data Comm, beginning the implementation of en route services that support the portion of flight at cruising altitudes. En route services are now fully operational at the Kansas City and Indianapolis Air Route Traffic Control Centers (ARTCCs) and are scheduled to be deployed to the remaining continental U.S. ARTCCs in the FY 2020–21 timeframe. Data Comm en route services will contribute to more efficient routes and a reduction in flight delays, resulting in increased operational efficiency and enhanced flight safety—all while reducing costs for airspace users. The FAA estimates that Data Comm will save aircraft operators more than $10 billion over the 30-year life cycle of the program. The FAA expects to save about $1 billion in future operating costs.

ADS-B

January 1, 2020, brought about a significant change to the National Airspace System, laying the groundwork for a safer and more efficient system that will help meet the predicted increase in air traffic in coming years and create the opportunity for future operational benefits. As of January 1, 2020, aircraft flying in most controlled airspace must be equipped to transmit their position using ADS-B Out, unless otherwise authorized by air traffic control. There are now more than 119,000 U.S. aircraft equipped with properly functioning ADS-B Out avionics.

ADS-B uses GPS to determine aircraft position more accurately and with faster updates than radar. The Equip 2020 Government-industry working group continues collaboration to eliminate equipage impediments for commercial and general aviation operators. Equipping with ADS-B In is not mandatory, but operators who install it experience benefits such as seeing the same traffic picture on their cockpit displays as controllers. General aviation operators who equip with ADS-B In also can view graphical weather and flight information delivered to the cockpit at no further cost.

To encourage ADS-B Out equipage within a portion of the general aviation community, the FAA began offering 20,000 $500 rebates in September 2016 to operators of U.S.-registered, fixed-wing, single-engine piston aircraft. The rebate incentive was intended to defray ADS-B equipment and installation costs. More than 10,200 pilots claimed the offer that ended one year after its start. Between October 12, 2018, and October 11, 2019, the FAA resumed offering the remaining $500 rebates, all of which were reserved. The rebate, coupled with extensive outreach activities, contributed to a steady increase in properly equipped aircraft.

The FAA will continue to conduct comprehensive educational outreach as the aviation community works to meet the ADS-B Out mandate and as aircraft continue to equip over time in order to fly in ADS-B–rule airspace.

Performance Based Navigation

Performance Based Navigation (PBN) uses satellites and onboard equipment for navigation procedures that are more precise and accurate than using standard

avionics and ground-based navigation aids. The types of routes and procedures an aircraft can fly depend on equipment performance level and pilot training.

The FAA has published more than 9,300 PBN departure, arrival, and approach procedures as well as low- and high-altitude PBN routes. These procedures provide precise flight paths across the United States that are much more direct than the legacy flight paths they replace, which zigzag over ground-based navigation aids. The PBN NAS Navigation Strategy 2016 (*http://www.faa.gov/nextgen/media/PBN_NAS_NAV.pdf*) outlines the FAA's plans for moving to a PBN-centric NAS.

PBN benefits include the following:

- Increased safety through repeatable and predictable flight paths when accessing airspace near obstacles and terrain, and with vertical guidance for more stable approaches.
- Improved airport and airspace access in all weather conditions.
- Reduced delays at airports and in certain congested airspace by using new parallel routes, newly enabled ingress/egress points around busy terminal areas, and improved flight rerouting capabilities that make better use of closely spaced procedures and airspace.
- Improved efficiency through more direct routes, especially at lower flight altitudes.

PBN's Area Navigation (RNAV) and Required Navigation Performance (RNP) provide environmental benefits through reduced fuel consumption and emissions. The FAA estimates that since airlines started flying new RNAV approaches into Minneapolis in March 2015, PBN saved more than 5.8 million gallons of fuel and prevented more than 57,000 metric tons of carbon dioxide from entering the atmosphere. In Denver, RNP approaches save Southwest, United, and Frontier airlines more than 100 gallons of fuel per flight.

System Wide Information Management

To function smoothly, NAS users must share an increasing amount of flight and weather data. The System Wide Information Management (SWIM) information network provides the infrastructure for the exchange of digital data for aviation

stakeholders. The digital data delivery platform provides the foundation for fully implementing many NextGen operational improvements.

SWIM replaces many stand-alone computer interfaces that connected point to point. SWIM offers a modern, universally recognized data exchange through a single connection. The data format has been harmonized with domestic and international aviation communities. SWIM provides registered users with unprecedented access to data products with improved bandwidth and enhanced security. SWIM plays a critical role in the successful implementation of TBO.

Decision Support Systems

Controllers and traffic managers use decision support systems to help solve airspace, weather, and other constraints and optimize traffic flow across the NAS.

The primary tools for strategic flow, en route flow, and airport terminal/surface flow are the Traffic Flow Management System (TFMS), Time Based Flow Management (TBFM), and Terminal Flight Data Manager (TFDM). These systems are often referred to as the "3Ts."

Controllers and traffic managers use decision support systems to help solve constraints and optimize traffic flow across the NAS. A trio of major decision support systems work together to provide these functions.

The first of these systems, TBFM, uses time-based metering to better utilize NAS capacity by improving traffic flow management of aircraft approaching and departing congested airspace and airports. TBFM is operational at 20 air route traffic control centers and adapted for many major airports served by those centers. TBFM is a vital part of the NAS and enhances air traffic operations by reducing delays and increasing the efficiency of airline operations. Departure scheduling and en route metering functions of TBFM are in use across the NAS today and are being expanded with additional deployments. Expansion of time-based management tools to terminal facilities is planned over the coming years, with the development and deployment of Terminal Sequencing and Spacing (TSAS).

TFMS supports the FAA's Traffic Management personnel in providing efficiency-critical NAS services. Each day, traffic managers use TFMS to maintain near-real-time situational awareness and predict geographic areas that may experience

congestion due to capacity reductions or unusual demand increase. TFMS is used to facilitate collaborative planning and decision making to proactively plan impact mitigation strategies between the Air Traffic Control System Command Center, Traffic Management Units at all major air traffic control facilities (80 sites), and flight operators. In addition to the air traffic control facilities, there are an additional 39 remote sites located at other FAA, military, and Government installations. The FAA is working on TFMS enhancements to provide traffic managers with further advanced decision support as we move toward TBO.

TFDM is in development to deliver decision support capabilities, including a surface metering capability, for use by tower air traffic controllers and traffic managers. TFDM will integrate flight, surface surveillance, and traffic management information. TFDM will implement electronic flight strips and automate manual flight data processes to enable enhanced data sharing between the tower, en route, approach control, traffic flow management, and flight/airline operations centers. The FAA completed early implementation of portions of TFDM, including Advanced Electronic Flight Strips (AEFS). AEFS converts paper strips to electronic strips displayed to the controller. AEFS prototypes are working in Phoenix, Arizona; Cleveland, Ohio; and Charlotte, North Carolina. Full TFDM deployment will begin in 2020. The FAA plans to deploy TFDM at 89 towers across the country.

Together, TBFM, TFMS, TFDM, and forthcoming enhancements to these systems are key to the delivery of TBO.

Interagency Collaboration

In addition to collaboration with the aviation community through the NAC, the FAA promotes the acceptance and adoption of NextGen technologies and procedures through cooperation with Federal partner agencies.

The NextGen Executive Board, made up of senior executives from NextGen Federal partner agencies, is one of two bodies that guide interagency NextGen activities. The NextGen Executive Weather Panel is a forum for the FAA, NASA, and the Departments of Defense and Commerce to collaborate on weather-related research and development, policy, and implementation activities.

Internally in the FAA, the NextGen Management Board provides oversight of NextGen initiatives, including objectives, policy implications, and operational aspects of implementation. It approves new capabilities and makes recommendations to terminate or amend concepts.

UAS

Just as NextGen is transforming the NAS, Unmanned Aircraft Systems (UAS) are bringing unprecedented new opportunities for business and recreation. The number of UAS pilots in the NAS has grown dramatically. The challenge is to ensure that these new aircraft are integrated with crewed aircraft without compromising safety to people and property on the ground or in the air.

The FAA is working with NASA and other Federal and industry partners to safely integrate UAS into the NAS. Since the FAA implemented a new rule to permit small UAS-limited operations in U.S. airspace in August 2016, more than 80,000 individual drones have been registered for various commercial and Government purposes.

In the second quarter of 2017, the FAA launched a prototype version of the Low Altitude Authorization and Notification Capability (LAANC), which provides drones with access to controlled airspace near airports through near real-time processing of authorization requests. LAANC is an innovative partnership between industry and the FAA where we supply the source data and technical requirements and industry builds apps (many of which are compatible with smartphones) for commercial drone operators to plan their flights and access controlled airspace. The FAA developed the internal application that displays the authorizations to air traffic managers to provide awareness of authorized drone flights. Prior to LAANC, the manually processed authorizations had drone operators waiting more than 100 days. Since its 2017 launch at ten facilities, LAANC has expanded to include 400 facilities covering nearly 600 airports. To date, LAANC has processed more than 200,000 authorization requests and processes nearly 90 percent of all authorization requests to fly in controlled airspace. LAANC has vastly decreased the wait time for UAS pilots to obtain authorizations. LAANC signals a new way that the FAA is doing business with industry to solve new challenges.

The introduction of UAS affects existing and future aviation requirements from aircraft certification to ATM. NASA and the FAA established a UAS Traffic Management Research Transition Team to define and develop requirements and standards that will be necessary for safe and efficient integration of UAS.

Additional information about the FAA Office of NextGen, updates, reports, and other documents can be found at *https://www.faa.gov/nextgen*.

Commercial Space Transportation

In FY 2018, the FAA's Office of Commercial Space Transportation (AST) licensed 35 commercial space operations, including three licensed reentries, five cargo resupply missions to the International Space Station, and the first launch of humans to space from U.S. soil since the end of the Space Shuttle Program in 2011. Additionally, AST issued nine new launch licenses, including a Reusable Launch Operator license to Blue Origin for suborbital launches of its New Shepard launch vehicle, as well as 14 National Environmental Policy Act (NEPA)–related environmental documents. AST's safety inspectors conducted 543 inspections to ensure that launch and reentry operations did not jeopardize public safety.

In FY 2018, the FAA completed a number of successful demonstrations of the agency's Space Data Integrator (SDI) proof of concept, including demonstrations featuring the first integration of live data from a vehicle in orbit and during reentry and the first integration of live launch vehicle data, integration of a complete suborbital trajectory, and integration of data for multiple launch vehicle elements (booster and capsule). The FAA is developing an SDI to support launch and reentry operations in a way that will allow the FAA to reduce the amount of airspace required to be closed in advance of a mission, effectively respond to off-nominal scenarios in a timelier manner, and quickly release airspace back to the National Airspace System as the mission progresses. This technology is a building block for future technologies that will allow the FAA to move away from accommodating commercial space operations in the NAS to integrating them with other airspace users. Additional information about the FAA Office of Commercial Space Transportation, regulations, reports, and other documents can be found online at *https://www.faa.gov/about/office_org/headquarters_offices/ast/*.

Department of Commerce

DOC

During FY 2019, the Department of Commerce (DOC) took significant steps to advance the U.S. commercial space industry while continuing its essential role as a leading civilian operational space agency.

Office of Space Commerce

Consistent with Secretary Wilbur Ross's strategic plan objective to "Expand Commercial Space Activities," the Department increased the staffing of its Office of Space Commerce, participated in the meetings and activities of the National Space Council, and supported American companies operating in space. Per President Trump's Space Policy Directive–2 (SPD-2), the Department of Space Commerce proposed new rules to streamline commercial space export control regulations and the licensing of commercial remote sensing activities. Per Space Policy Directive–3 (SPD-3), the Department made progress toward the establishment of a new space situational awareness capability to support commercial space operators.

Secretary Ross or Deputy Secretary Karen Dunn Kelley participated in the three FY 2019 meetings of the National Space Council, reporting on the Department's implementation of SPD-2 and SPD-3 and accepting new tasks on U.S. space competitiveness and authorization of commercial space operations. The Office of Space Commerce coordinated the Department's implementation of Council recommendations and participation in White House deliberations on multiple space issues.

The Department engaged in continuous dialogue with U.S. space companies to understand and support their business needs. Secretary Ross and other Department leadership hosted a series of public events focusing on critical elements needed to

grow the U.S. space economy, including financial investment (December 2018), risk mitigation (March 2019), safety and sustainability (June 2019), and support from the Department (September 2019). The Department promoted U.S. industry interests while leading delegations to the United Nations Committee on the Peaceful Uses of Outer Space, U.S.-Thai civil space dialogue, and U.S.-European working group on satellite navigation market access.

Regulatory Streamlining Under SPD-2

In October 2019, as directed by SPD-2, Secretary Ross submitted to Congress a legislative proposal to establish a new Bureau of Space Commerce that would consolidate the Department's space regulatory authorities and provide a "one-stop shop" for the commercial space industry.

Through the Bureau of Industry and Security (BIS), the Department issued an Advance Notice of Proposed Rulemaking in March 2019, soliciting public comments to inform the streamlining of commercial space export control regulations. The Department also hosted an industry day in April 2019 and used the collected feedback to inform interagency deliberations on export control rule changes to be released in FY 2020.

Through the National Oceanic and Atmospheric Administration (NOAA), the Department proposed a complete rewrite of its rules on the licensing of private remote sensing space systems. NOAA issued a Notice of Proposed Rulemaking in May 2019 and hosted two public discussions of the proposal through its Advisory Committee on Commercial Remote Sensing. The industry feedback received through these processes led to further improvements in the final rule published in FY 2020.

In March 2019, Secretary Ross submitted a report to the President titled "Driving Space Commerce Through Effective Spectrum Policy" in March 2019. The report makes recommendations for improving the global competitiveness of the U.S. space sector through radio frequency spectrum policies, regulation, and U.S. activities at the International Telecommunications Union and other multilateral forums.

In November 2018, the Federal Communications Commission (FCC) issued an order waiving its licensing requirements for non-Federal receivers of Europe's Galileo satellite navigation signals. The Department played a significant role in

advocating for the waiver, which the National Telecommunications and Information Administration (NTIA) had recommended to the FCC in January 2015.

Space Situational Awareness Under SPD-3

Through the Office of Space Commerce, the Department developed and began implementing a roadmap for its future role, under SPD-3, providing space situational awareness (SSA) data and services to commercial space operators. In April 2019, the Office issued a Request for Information to collect information on commercial SSA capabilities and future regulatory requirements.

In the second half of FY 2019, the Department established a continuous Commerce presence at the Department of Defense's existing SSA operations center at Vandenberg Air Force Base in California. The Department also obtained access to a cloud-based data management platform developed by the Department of Defense. It used the platform to demonstrate SSA data dissemination and fusion concepts in cooperation with commercial data providers.

The Department promoted the adoption of best practices for space safety through a variety of international forums, including the United Nations; bilateral space dialogues with Japan, Europe, Indonesia, the United Arab Emirates, and Thailand; and major SSA conferences, including the June 2019 Space Enterprise Summit organized by the Departments of State and Commerce. In May 2019, Secretary Ross and the Deputy Prime Minister of Luxembourg signed a Memorandum of Understanding on space cooperation, to include collaboration on space debris mitigation.

Civil Satellite Operations

During FY 2019, the Department continued to participate in the national management of the Global Positioning System (GPS) as a member of the National Executive Committee for Space-Based Positioning, Navigation, and Timing. The Office of Space Commerce continued to host the physical offices of the Committee as well as the *https://www.gps.gov/* website, which remained the leading source of online information about GPS.

National Oceanic and Atmospheric Administration

In FY 2019, NOAA's satellites remained as critical as ever, monitoring the wildfires in the western United States and Canada; hurricanes in the Gulf of Mexico and the Atlantic and Pacific oceans; and one of the hottest years on record. Twenty-four-hour global coverage from NOAA's satellites provides the public and partners, such as the National Weather Service, with a continuous stream of information used in preparation for events impacting our weather, oceans, and climate. NOAA manages and operates geostationary environmental satellites and low-Earth orbiting satellites, as well as a deep space satellite for space weather monitoring and forecasting. Below is a summary of major accomplishments regarding new NOAA and partner satellite assets in FY 2019.

Geostationary Satellites

NOAA's Geostationary Operational Environmental Satellites, known as the GOES-R Series, provides advanced imagery and atmospheric measurements of Earth's Western Hemisphere, real-time mapping of lightning activity, and improved monitoring of solar activity and space weather.

GOES-17, formerly GOES-S, became fully operational as NOAA's GOES West satellite on February 12, 2019. The second of NOAA's advanced geostationary weather satellites, GOES West provides high-resolution real-time visible and infrared imagery of the West Coast of the continental United States, Alaska, Hawaii, and much of the Pacific Ocean, and it operates in conjunction with its sister satellite, GOES East (GOES-16), which has the same instruments and capabilities. Until recently, high-quality data coverage of the Pacific Ocean was sparse, but now GOES West provides forecasters with access to more detailed views of high-impact weather systems, along with environmental hazards such as wildfire smoke, volcanic ash, and more. GOES-17 has been especially valuable to Alaska, where NOAA's older geostationary satellites provided far less coverage.

Following is a list of NOAA geostationary satellites in use with date launched:

- GOES West (GOES-S/GOES-17), March 1, 2018
- GOES East (GOES-R/GOES-16), November 19, 2016

- GOES-14, June 27, 2009

Low-Earth Orbiting Satellites

NOAA's primary low-Earth orbiting environmental satellites, NOAA-20 and Suomi National Polar-orbiting Partnership (Suomi NPP), provide full global coverage with advanced sensors for weather and climate data, collecting information on temperature, atmospheric conditions, wind speed, cloud formation, and drought conditions over the entire Earth. All major numerical weather prediction (NWP) centers around the world use this information as the basis of nearly every medium-term weather forecast.

The Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) constellation provides precision radio occultation (RO) soundings to support improved numerical weather prediction model forecasts. On June 25, 2019, NOAA supported the successful launch of COSMIC-2—known in Taiwan as FORMOSAT-7—in joint collaboration with Taiwan, the National Science Foundation (NSF), NASA, the United States Air Force (USAF), and the University Corporation for Atmospheric Research (UCAR). The mission consists of six satellites designed to improve weather forecasts and space weather monitoring via state-of-the-art instruments that provide improved precision and performance, as well as five times the number of measurement capabilities, with near-real-time numerical weather prediction. By measuring minute bending in the GPS signal, the information collected by COSMIC-2 satellites provides meteorologists with details about Earth's atmosphere—such as temperature, pressure, density, and water vapor—that will help meteorologists better observe, study, and forecast severe storms. Additionally, COSMIC-2 monitors solar activity that can disrupt the power delivered to individuals' homes and provides global temperature documentation to help scientists understand long-term climate changes on Earth.

Metop is a series of three polar-orbiting meteorological satellites that form the space segment component of the overall European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) Polar System. The third in the series, Metop-C, recently launched on November 7, 2018, is a new state-of-the-art polar-orbiting satellite that helps improve complex weather forecasts and

models as well as long-term climate assessments. This satellite works together with its predecessors (Metop-A and -B), as well as Suomi-NPP, NOAA-20, and NOAA legacy satellites, to collect more precise weather data as we continue to improve forecast errors from combined satellite observations incorporated into models. NOAA supplied four of the 13 instruments onboard the satellite, including two microwave emitters that measure global atmospheric temperature, humidity, and sea ice, as well as a visible/infrared radiometer that delivers imagery of clouds, oceans, ice, and land surfaces. The last instrument is the Space Environment Monitor (SEM), which monitors space plasma and radiation around the spacecraft. Additionally, the satellite's instruments provide new and improved observations on atmospheric aerosols, CO and SO_2, soil moisture, and radio occultation soundings that can penetrate deeper into the lower troposphere. The launch was a collaborative effort between NOAA, NASA, and international partners at EUMETSAT and the European Space Agency.

The following is a list of NOAA low-Earth orbiting satellites in use with date launched:

- NOAA-20 (Joint Polar Satellite System [JPSS]-1), November 18, 2017
- Suomi-NPP, October 28, 2011
- NOAA-19, February 6, 2009
- NOAA-18, May 20, 2005
- NOAA-15, May 13, 1998

Following are the partnership satellites with which NOAA partnered for launch and/or operations, with date launched:

- COSMIC-2, June 25, 2019
- Metop-C, November 6, 2018
- Jason-3, January 17, 2016

Deep Space (Lagrange Point–1) Satellites

Geomagnetic storms are major disturbances of Earth's magnetosphere caused by shock waves in the solar wind. Geomagnetic storms are the costliest type of space weather events as they can cause widespread damage to power grids, satellites, and communication and navigation systems. The Deep Space Climate Observatory

(DSCOVR) mission is NOAA's first operational deep space mission. The satellite has become America's primary warning system for solar magnetic storms and solar wind data while giving Earth scientists a unique vantage point for studies of the planet's atmosphere and climate.

NOAA is partnering with the Naval Research Laboratory (NRL) to build a Compact Coronagraph (CCOR) for future space weather observations. In FY 2019, NRL's CCOR completed its Critical Design Review, which affirmed that the design meets requirements and is ready to proceed with full-scale fabrication, assembly, integration, and testing.

National Institute of Standards and Technology

In FY 2019, the National Institute of Standards and Technology (NIST) continued to provide wide-ranging contributions to the aerospace industry, academia, and Federal agencies with the research, standards, products, services, and guidance needed to advance the President's aeronautics and space agenda.

NIST's primary contributions came in the forms of calibrations, technology development, and standards development. These contributions are grouped into six main categories: 1) advanced manufacturing for aerospace applications, 2) aerospace systems and supplies, 3) aerospace communications, 4) calibrations and sensor development for satellites, 5) support for terrestrial research, and 6) support for extraterrestrial research.

Advanced Manufacturing for Aerospace Applications

In FY 2019, NIST used measurement expertise in mass, force, networking, and other areas to partner with Boeing, Honeywell Aerospace, Lockheed Martin, Northrop Grumman, General Electric Aviation, Rolls-Royce, United Technologies Aerospace, and others. In addition to providing calibration support, NIST's broad portfolio in advanced manufacturing helped aerospace manufacturing companies address needs in many sectors, including additive manufacturing, collaborative robotics, smart manufacturing, cybersecurity in manufacturing environments, supply-chain logistics, and large-scale manufacturing.

NIST continued to provide the tools, methodologies, standards, and measurement services needed by aerospace parts manufacturers, assemblers, and NASA to maintain their accurate and traceable use of the International System of Units (SI) units of length, mass, force, acceleration, and sound pressure, as well as the electrical SI units of resistance, capacitance, inductance, voltage, and current. For instance, NIST provided load cell calibrations and provided manufacturers with a traceable means to analyze the integrity of airplane wing box structures. Other NIST calibration-related services included the use of NIST-calibrated weights to support wind tunnel applications; the weighing of airplanes; and torque, pressure, and force measurements. Also, NIST performed calibrations of many standard resistors, capacitors, and inductors for U.S. aerospace companies and DOD primary calibration labs to ensure the accuracy and traceability of their electronic test equipment, and, consequently, the calibration accuracy of the thousands of flight avionics systems that are tested and verified using these calibration instruments.

NIST worked with Boeing, National Research Council (NRC) Canada, and others on methods to quantify the performance of laser scanning technology for dimensional measurements. Laser scanning is a key new technology for advanced manufacturing that offers potential cost savings, increased measurement throughput, and high data densities, and it is especially suited for the manufacture of large structures such as aircraft components. Key traceability questions remain to be addressed, impeding universal adoption. The NIST work includes developing mathematical error models of these instruments, developing test procedures that capture these error sources, and leading the development of national and international standards. In December 2017, NIST published an ASTM documentary standard (ASTM E3125-17) for the performance evaluation of laser scanners. NIST led the standards development work, but it was supported by Boeing; Newport News Shipbuilding; NRC Canada; and all leading manufacturers of laser scanners, such as FARO, Surphaser, Leica, Trimble, and Z&F.

NIST is working with aerospace companies such as Boeing, Airbus, Spirit Aero, Gulfstream, United Technologies, etc., on updates to the American Society of Mechanical Engineers (ASME) documentary standard for the performance evaluation of laser trackers, important dimensional measurement technology for the manufacture, testing, and monitoring of large structures. The effort to revise the

documentary standard came at the request of users of the standard, including those in the aerospace industry, for a more comprehensive interim test. NIST is developing the interim test using mathematical error models with additional input from users and manufacturers of the technology. Interim testing can be used to verify the performance of the laser trackers before they are used for critical measurements. This testing is especially important for systems like laser trackers that are portable and can be used in a range of different environmental conditions. NIST leads this effort with participation from all leading laser tracker manufacturers (API, FARO, Hexagon), the defense/communications industry (Lockheed Martin, Harris Corp., General Dynamics, Orbital ATK), nuclear power companies (BWXT), other National Measurement Institutes (NRC Canada, INMETRO [Brazil], CENAM [Mexico]), etc.

NIST continued its program in laser materials processing to implement inline process monitoring and offline characterization in laser welding to reduce development and operating costs and expand markets for laser-welding applications. In collaboration with Haynes International, NIST developed weldability tests, performing hardness and strain mapping, and carried out fatigue testing of high-temperature, corrosion-resistant nickel-based alloys, which are used in engines, pumps, compressors, and other high-temperature applications within the aerospace industry.

Additive manufacturing (AM) processes are proving to be key processing technologies with great potential in aerospace applications—for example, highly complex components such as aircraft engine fuel injectors, turbine blades with complex internal cooling channels, and lightweight structural components. NIST continued its program in measurement science in additive manufacturing by developing and deploying measurement methods and tools to enable rapid design-to-product transformations through advances in material, machine, and process characterization, as well as in-process sensing, monitoring, and control of metal additive manufacturing. In FY 2019, NIST continued collaboration with NASA and the FAA to organize a Technical Interchange Meeting with the leading aerospace Original Equipment Manufacturers (OEMs) to determine the maturity level of physics-based models in establishing process/part qualification. In FY 2019, NIST also organized a workshop titled "AM Materials Database and Data Analytics," providing hands-on

sessions to the AM community, including aerospace OEMs. NIST also collaborated with researchers from the Air Force Academy to characterize residual stresses in aluminum alloy samples originating during supersonic particle deposition (SPD), a characteristic of the Cold Spray Process (CSP) that is well suited for the repair and restoration of nonstructural aircraft components.

NIST continues to work in the development of advanced nanometrology for nanomanufacturing. The aerospace industry is interested in the potential benefits of nanotechnology. The development of accurate nanometrology of small particles and structures is critical to the success of this effort. For example, a Reference Material has been made available for the scale calibration of optical, scanning probe, and scanning particle beam instruments to the same dimensional standard. The use of this standard has also been extended to the measurement and monitoring of beam-induced contamination in scanned particle beam instruments. Using this standard and the methods developed, NIST has virtually eliminated the deposition of contamination on the specimen, which is a common artifact in these instruments (which are critical to imaging, measurement, and characterization for nanotechnology). In addition, these methods have applications in other areas, such as cleaning optical surfaces. NIST is also conducting research to characterize and monitor instrumentation performance and standardization to ensure accurate dimensional metrology of carbon composites and carbon nanotubes. Nanocomposite material offers the advantage of lighter airframes, giving better fuel economy; however, it still needs to be determined if the material provides the high strength and durability required. To facilitate this, NIST developed a new 3D scanning electron microscope imaging technique to help to determine the carbon nanotube loading in composite materials.

NIST continued to provide leadership and contributions to the standards-development organizations, such as ASTM, the American Society of Mechanical Engineers (ASME), and the Society of Automotive Engineers (SAE), that provide specifications and best practices to the aerospace industry.

Much of NIST's support for the aerospace supply chain came with interactions through the suppliers themselves. In FY 2019, the Hollings Manufacturing Extension Partnership (MEP) National Network engaged in 336 projects with 172 individual manufacturing clients designated with an aerospace North American

Industry Classification System number (NAICS 3364). The MEP post-project, a follow-up survey of aerospace NAICS companies, revealed that MEP services had resulted in the creation or retention of 4,956 aerospace jobs, over $170 million in new sales, over $209 million in retained sales, over $131 million in new investment, and over $18 million in cost savings.

Table 1. NIST MEP Aerospace Impact.

Total Sales	$379,925,882.00
Total Cost Savings	$18,443,740.00
Total Investment (Products and Processes [P&P], Plant and Equipment [P&E], Information Technology [IT], Workforce, Other)	$131,025,121.00
Total Jobs	4,956

Aerospace Systems and Supplies

NIST's contributions to the manufacturing sector were complemented with support for the design, development, and calibration of aerospace systems and supplies. Contributions included collaborative robotics, material development for advanced applications, fuel development, weapons calibrations, and thrust calibrations.

In support of materials development and selection, NIST provided technical input to manufacturers (airframe, chemical, and fire-suppression equipment) on new blends to replace current materials used for aircraft cargo-bay fire suppression. NIST also worked with NASA researchers to develop ASTM test methods to evaluate the performance of thermal insulating materials for spacecraft.

In support of equipment development, NIST performed advanced measurements and characterizations of high-efficiency solar cells deployed for space and terrestrial power applications in collaboration with space solar cell manufacturer Hamadanid. NIST worked with SolAero Technologies Corporation to "space-qualify" their solar cells. SolAero sent batches of solar cells for irradiation by an electron beam from the NIST Van de Graaff accelerator, where exposure experienced by a satellite over several decades in Earth orbit may be delivered in less than one hour. The NIST Clinac and Van de Graaff accelerators characterized the electron energy response of charged-particle detection systems developed by Assurance

Technology Corporation for the joint NASA-NOAA Geostationary Operational Environmental Satellites (GOES) program. These detector systems compose part of the onboard payload of GOES satellites and provide critical information on the charged-particle environment in Earth orbit. Calibrations performed at NIST are crucial for providing the most accurate spectral details for more useful space weather monitoring and forecasting.

NIST, members from the aerospace field (Thermacore, Marshall Space Flight Center, and the Air Force Academy) and members from academia (the University of Tennessee, the University of Missouri, and Michigan Technology University) used the NIST neutron facility resources to perform unique measurements on aerospace-related systems. These groups studied the conservation of cryogenic fuels (to help improve the storage and transfer of these cryogens in space) by measuring the evaporation and condensation coefficients of cryogenic propellants.

NIST continued efforts to simplify spacecraft cryogenic requirements through on-chip electrical cooling of cryogenic detectors, providing a final on-chip stage able to cool from 0.3 kelvin to 0.1 kelvin, well matched to cryogenic detectors for future NASA missions.

NIST developed airspeed, hydrocarbon liquid-flow, and gas-flow measurements that supported equipment and supply development in the aerospace sector. The airspeed calibration service performed calibrations of anemometers used at airports, on aircraft, and in wind tunnels used for testing new aircraft. The hydrocarbon liquid calibration service calibrated flow meters that are used to meter jet fuel, for example, turbine meters used to evaluate jet engine performance on test stands. The Laser Power and Energy Meter Calibrations project provided 30–70 calibrations to the aerospace industry and DOD customers, supporting both laser weapons systems and target designation systems.

NIST performed radiometric measurements of the collimated output infrared beam from a space simulation chamber used at Raytheon Missile Systems, Inc., for the calibration of infrared remote sensing systems for the Missile Defense Agency. For this work, NIST utilized the NIST-developed Missile Defense Transfer Radiometer (MDXR), a portable cryogenic radiometer. NIST is also making progress on the development of the next-generation User Transfer Radiometer (UXR), which has additional capabilities and eventually will replace the MDXR.

Aerospace Communications

NIST contributed to the measurement and development of multiple technologies associated with aerospace communications, including advancements in high-precision clocks used in communication.

In FY 2019, NIST collaborated with NASA's Jet Propulsion Laboratory (JPL) on the development of superconducting nanowire single-photon detectors (SNSPDs) for use in space communications and various quantum information experiments. NIST and JPL were able to demonstrate a small array of SNSPDs to increase the device area, an essential development for future usage in laser communication systems and exoplanet searches via mid-infrared spectroscopy. Additional efforts by NIST and JPL to improve SNSPDs included optimizing ultraviolet light detection and exploring the use of new material in SNSPD development.

The NIST antenna calibration facility was instrumental in performing measurements that led to the creation of the space satellite company and small business Orbital Micro Systems (OMS). The calibrated antenna pattern data provided by NIST allowed better accuracy of their instruments, including the development and characterization of additive manufactured antennas, and significantly reducing manufacturing costs for OMS. This work led to the first commercially owned and operated passive microwave radiometer flown in space, with successful deployment from the International Space Station on July 20, 2019. OMS customers rely on the accuracy of their radiometric measurements to manage terrestrial and weather-related risks.

The Air Force is leveraging NIST in its development of a test system to explore the use of the comb-based time transfer for future optically cross-linked GPS satellites. In support of these efforts, NIST transferred frequency comb designs to Boeing to help advance future space-based optical clocks. NIST also transferred its comb-based optical two-way time-frequency transfer technology to the Air Force and its contractors. NIST is also supporting SBIR efforts with Vector Atomic and Freedom Photonics to miniaturize key time-transfer components.

NIST participated in NASA's support of the European Space Agency's (ESA) Atomic Clock Ensemble in Space (ACES) program and the Space Optical Clock (SOC) program, as a high-precision atomic clock for the ISS will support

tests of fundamental physics and provide high-accuracy global comparisons of ground clocks.

Calibrations and Sensor Development for Satellites

NIST's contributions to satellite and other space hardware came in both technology development and measurement calibration.

NASA's next-generation suborbital and satellite observatories require new detectors with improved sensitivity and scalability. With NASA funding, NIST continued to improve two types of sensors: superconducting transition-edge sensors (TESes) and microwave kinetic-inductance detectors (MKIDs). These technologies supported the following NASA projects: the Balloon-borne Large-Aperture Submillimeter Telescope–The Next Generation (BLAST-TNG), SPIDER, Lite satellite for the studies of B-mode polarization and Inflation from cosmic background Radiation Detection (LiteBIRD), and other next-generation satellites. These sensor technologies offer new capabilities for the detection of electromagnetic signals across the spectrum, from millimeter waves like the cosmic microwave background (CMB) through x-rays, and can help research aspects of star formation and the evolution of galaxies. Improvements to TES technology enable a number of new ground-based instruments, including the vast CMB detector arrays that will be deployed in the Simons Observatory.

With NASA funding, NIST continued the development of superconducting quantum interference devices (SQUIDs) and SQUID-based multiplexers to read out large arrays of TES detectors in a manageable number of output channels. NIST provided SQUID systems to researchers at NASA Centers (Goddard Space Flight Center and the Jet Propulsion Laboratory) and institutions working on NASA-funded projects (California Polytechnic Institute; Stanford University; the Massachusetts Institute of Technology; the University of California, Berkeley; Princeton University; Cornell University; and others). SQUID technology was incorporated into the recently launched sounding rocket Micro-X and into the focal-plane demonstration system for the Advanced Telescope for High-ENergy Astrophysics (ATHENA), a European Space Agency x-ray satellite mission. NIST

also used SQUID expertise to assist NASA Goddard in the development of new magnetic micro-calorimeters.

In support of satellite and related missions, NIST provided calibration services and research to enable the aerospace industry and Government agencies to obtain temperature, pressure, vacuum, humidity, and leak thermodynamic measurements traceable to international standards. Calibrations provided traceability to maintain quality systems, to maintain process control, and to qualify instrumentation for flight and space travel. NIST's Synchrotron Ultraviolet Radiation Facility (SURF) III provided a source of soft x-rays and extreme ultraviolet (EUV) light to calibrate mirrors, filters, detectors, and spectrometers used in NASA and NOAA spacecraft.

Support for Terrestrial Research

NIST measurement science provided support to the development and calibration of instrumentation used in researching Earth's surface and atmosphere.

NIST's SURF III was used as an absolute calculable source of radiation spanning the spectrum from soft x-rays to the blue end of the visible band to calibrate spectrometers and other optical elements used in NASA and NOAA spacecraft. This year, SURF III staff collaborated with a team from the Laboratory of Atmospheric and Space Physics (LASP) at the University of Colorado to calibrate the rocket-borne instruments used to check and maintain the accuracy of the EUV Variability Experiment (EVE) instrumentation flying aboard NASA's Solar Dynamics Observatory (SDO) satellite and new modules of the EUV and X-ray Irradiance Sensor (EXIS) for future NOAA GOES-R series satellite missions. These instruments are designed to study the soft x-ray and EUV solar irradiance and its variability. The NASA EVE measurements are important to the National Space Weather Program (NSWP), which tracks solar storms that impact space-based communications and navigation technologies, and the NOAA EXIS measurements provide NOAA with data on solar inputs to Earth's atmosphere, which are essential for climate modeling.

NIST collaborated with LASP scientists to study the cause of the rapid degradation seen in some of the solar-observing optical components aboard missions such

as the GOES-R series and the SDO. Observed losses in EUV transmission on the order of some ten percent or more per year require frequent and expensive rocket under-flight missions to recalibrate the satellite instruments. For a long time, many in the space science community believed that the degradation was a result of the optics being carbonized by the reaction of the solar ultraviolet (UV) with the adsorbed organics coming from outgassing materials in the spacecraft. Using UV radiation from SURF III to simulate the solar spectrum, the collaboration demonstrated that carbonization was highly unlikely to be the cause. This finding turned the focus onto oxidation caused by UV-activated adsorbed water as the possible culprit. This research is continuing, with the goal of a definitive determination of the cause and possible means of mitigation.

NIST continued its collaboration with NOAA on the calibration of the Marine Optical Buoy (MOBY) used in the System Vicarious Calibration (SVC) of ocean-color measurements provided by satellite sensors. NIST participates in the MOBY Refresh effort, which is resulting in a new optical design and other improvements that will reduce the overall measurement uncertainties and allow the current system, which is beyond its design lifetime, to be retired. The MOBY team and NIST were selected by NASA to start a new project that will result in the design of Refresh and the concept of MOBY-Net to be implemented as a second ocean-color SVC site. NIST's Carbon Nanotube Electrical Substitution Radiometer (CNT ESR), built in collaboration with LASP and NASA's Earth Science Technology Office, successfully launched into space on the Compact Solar Irradiance Monitor (CSIM) instrument. The CNT ESR is currently performing absolute measurements of solar power as a function of wavelength to serve as a baseline for weather and climate monitoring. The Compact Total Irradiance Monitor (CTIM, formerly the Carbon Absolute Electrical Substitution Radiometer, CAESR) has the purpose of performing absolute measurements of total broadband solar power that will provide continuity in total solar irradiance measurements for weather and climate monitoring. The teams extended the technologies used in the CSIM and CTIM flight instruments into a Broadband Absolute Bolometer Array (BABAR). The BABAR aims to improve accuracy and decrease instrument size (therefore reducing cost) for solar science, fire detection from space- and airborne platforms, severe

weather monitoring from space- and airborne platforms, and Earth radiation budget measurements.

Support for Extraterrestrial Research

NIST's support for extraterrestrial research included providing support and measurements for extraterrestrial bodies, providing support and measurement for the equipment used to observe them, and providing the data for measurements.

An ongoing collaboration with a group of researchers from JPL studied the penetration of high-energy electron beams into the ice of Europa's surface to assess damage to organic molecules. This work will help determine the necessary ice depths at which microbes could survive on Europa's surface.

NIST is working in collaboration with the University of Maryland on a project funded under NASA's Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO) Program to adapt a novel NIST-developed neutron detector to enable interplanetary probes to detect water and other hydrogenous materials near the surface of planets or moons. Compared to other detectors presently used in this mission space, the NIST detector should use less power, have simpler and more reliable support electronics, and be more mechanically robust. In addition, NIST has applied its simultaneous Neutron/X-Ray Tomography system (NeXT) to measure the hydrogen distribution in meteorites provided by the Lunar and Planetary Institute. These ongoing studies aid researchers in determining the water content of the solar system.

NIST, in partnership with NASA, the University of Maryland Baltimore County, and the University of Guelph, made the most accurate measurements ever of the spectral irradiance from the Moon in the visible-to-near-infrared from a NASA ER-2 high-altitude aircraft. NIST and its partners had the goal of enabling the Moon to serve as a calibration source for satellite sensors while they are in space. A team of Physical Measurement Laboratory (PML) scientists from the Sensor Science Division developed a specialized instrument, called Air-LUSI (Lunar Spectral Irradiance), over the past two years. This involved integrating a NIST-calibrated spectrometer, integrating a sphere and custom-designed telescope system into a wing-pod of the ER-2 aircraft, recalibrating it on-site at NASA

Armstrong Flight Research Center in Palmdale, California, and programming its computer to operate autonomously to track the moon and measure lunar irradiance during the flight. This year the NASA ER-2 flew the NIST Air-LUSI instrument on five consecutive nights to provide data that improved upon engineering data measured during one night last year. These data will act as tie points for validating/correcting the ongoing NIST mountain-based lunar-irradiance measurements.

NIST, with partial funding from NASA, provided quality assessment of the atomic data used by astronomers who are interpreting observations from NASA's land- and space-based missions, including the Hubble Space Telescope, the Chandra X-ray Observatory, the Far Ultraviolet Spectroscopic Explorer, and the Spitzer Infrared Observatory. In 2019, NIST provided results for neutral and ionized manganese, iron, strontium, and other elements of particularly strong current interest and disseminated them publicly through a new release of its online Atomic Spectra Database, v.5.7 (*http://physics.nist.gov/asd*). NIST also initiated the development of a new database of lanthanide opacities, which are highly important for the analysis of kilonova events (neutron star mergers).

NIST worked with the Space Science Laboratory and Sensor Sciences, LLC, to develop large-area, high-resolution plate detectors used to help x-ray telescopes peer into space. With support from NASA and the NSF, NIST developed frequency combs that support the detection of Earth-like planets around distant stars. These unique frequency combs, with spectral bandwidth spanning 500 to 1,000 nanometers and 30-gigahertz mode spacing, serve as a set of reference markers for high-precision astronomical spectrographs. The team completed proof-of-concept experiments at the NASA Infrared Telescope Facility and the Keck-II Telescope. In the past year, NIST also supported a new 30-gigahertz "Astro-comb" at the Hobby-Eberly Telescope, which is located at the McDonald Observatory in the Davis Mountains of Texas. This infrared-based system validated the detection of a Neptune-sized exoplanet orbiting an M-dwarf star (the most common type of star in our galaxy).

International Trade Administration

Industry and Trade Policy

The Office of Transportation and Machinery (OTM) continues to pursue multiple paths to promote exports of products and services that support the Next Generation Air Transportation System. OTM created and published an online NextGen Solutions Vendors Guide to help foreign customers identify U.S. companies that can provide products that meet the requirements of the International Civil Aviation Organization's (ICAO) Aviation System Block Upgrade (ASBU) technology roadmaps. The Guide currently is being transferred to the Salesforce platform, which will enable a more customer-friendly interface and provide end-to-end tracking and communication between vendors, customers, and relevant International Trade Administration (ITA) staff. Moreover, this new NextGen ATM Toolkit will allow U.S. companies to indicate, if they so choose, that they are current contractors with the FAA.

OTM participates in the World Air Traffic Management Congress in Madrid, Spain. OTM has worked with the FAA, industry, and the Air Traffic Control Association (ATCA) to emphasize U.S. technical capabilities to the global audience that attends. The Congress represents an opportunity to learn about the specific air navigation procurement needs of particular countries, to counsel individual companies on NextGen-related prospects as well as Commerce services, and to recruit participants for the NextGen Solutions Vendors Guide and potential applicants to the Industry Trade Advisory Committee on Aerospace Equipment (ITAC 1).

OTM participates in multiple forums regarding the operations and industry development of Unmanned Aircraft Systems (UAS). OTM represents ITA on the UAS Executive Committee (UAS EXCOM)—the interagency committee that addresses UAS policy writ large across the U.S. Government. OTM also serves on the UAS Senior Steering Group (UAS SSG), which carries out policy initiatives derived from the UAS EXCOM. On the SSG, OTM provides industry perspective through the SSG and related activities and chairs a working group to address data security concerns regarding foreign-made UAS operated by the

U.S. Government. OTM also represents ITA on the Unmanned Aircraft Systems Standards Collaborative (UASSC) hosted by the American National Standards Institute (ANSI). The UASSC coordinates the development of standards and conformity assessment programs needed to facilitate the safe integration of UAS into the National Airspace System (NAS) of the United States. On the UASSC, OTM participates in the UASSC Critical Infrastructure and Environment Working Group, with a focus on wide-area inspection, and works with the UASSC to promote international coordination and adaptability to foster the growth of the UAS market worldwide.

Throughout the year, OTM organized and led six meetings of ITAC 1. The Committee provides advice to the Secretary of Commerce and the U.S. Trade Representative on aerospace-related trade policy issues. This year, the Committee provided advisory opinions to the Secretary of Commerce and the U.S. Trade Representative concerning the U.S.–European Union (EU) and U.S.-Japan free-trade agreement negotiations.

ITA continues to support the Office of the U.S. Trade Representative on issues relating to the enforcement of U.S. rights under the World Trade Organization concerning trade in civil aircraft. In particular, OTM provided support in the ongoing U.S.-EU trade dispute over subsidies to manufacturers of large civil aircraft, providing industry expertise in areas relating to changes in the market and actions of the major stakeholders. OTM reviewed draft lists of items that may be included on tariff lists in response to the WTO's decision against Airbus.

ITA's OTM and Office of Finance and Insurance Industries (OFII) continued to participate in the Group on the Sector Understanding on Export Credits for Civil Aircraft (the "Aircraft Sector Understanding" or ASU) at the Organization for Economic Cooperation and Development (OECD). The governments of almost all countries with major aircraft manufacturers are signatories to the ASU, an annex to the OECD Arrangement on Officially Supported Export Credits, which establishes rules for export credit agencies. The OECD rules aim to ensure that government-provided export financing is not a competitive factor in civil-aircraft sales competitions. Industry feedback and available data on usage of the latest version of the ASU, which was finalized in 2011 and was scheduled for review in November 2019, suggest that the agreement is working as intended, although financing levels

declined significantly due to unrelated disruptions in both U.S. and European export credit support for aircraft exports. Notably, this included the Export-Import Bank's (EXIM) inability to approve large (over $10 million) transactions due to its continued lack of a quorum on its Board of Directors in 2019. As a member of the U.S. delegation, ITA helped ensure that the interests of the industry were addressed during the 2011 ASU negotiations, continues to monitor implementation, and will participate in any review. ITA also closely monitored conditions in the aircraft finance market and provided advice on the importance of restoring EXIM to full functionality with respect to the aerospace industry and its supply chain.

ITA and NOAA continued their active participation in the implementation of the current National Space Council and related policies, which include industrial base and competitiveness issues. To ensure that commercial interests continue to be adequately addressed, ITA and NOAA continued to ensure that all of the policies' implementation actions will improve the U.S. industry's competitiveness, stimulate the American economy, increase exports, and create U.S. jobs.

ITA continued to play an important role in promoting U.S. aerospace trade interests as the industry faced mounting competition from abroad. ITA participated in and organized trade events and provided advocacy to support U.S. companies in international aerospace competitions, including commercial sales for aircraft, helicopters, airport construction, communications, remote sensing satellites, commercial projects, and air traffic management projects. At the close of FY 2019, ITA's Advocacy Center had 33 active space-related cases with a total project value of $3.2 billion and U.S. export content of $2.9 billion. The Advocacy Center also had 400 active cases in the aerospace and defense sectors.

In May 2019, ITA's U.S. Export Assistance Center in Hartford, Connecticut, hosted an "International Space Trade Summit" to connect U.S. commercial space suppliers with buyers from the governments and industries of Canada, Australia, New Zealand, and the United Kingdom. The goal of this first-ever event was to bring advanced manufacturing and high-technology supply-chain companies into the global space sector by identifying opportunities and educating participants on regulations and programs.

In June 2019, ITA organized and supported the Commerce Department's participation in the Paris Air Show and arranged senior-level meetings with foreign

government and industry officials as well as U.S. industry executives. Through a Strategic Partnership with Kallman Worldwide, ITA hosted numerous educational briefings at the show, which highlighted the 50th anniversary of the Apollo 11 Moon landing. Additionally, ITA/OTM met with numerous U.S. and foreign government and industry officials to discuss ongoing policy issues impacting the competitiveness of U.S. industry.

Industry and Trade Promotion

ITA's Global Aerospace and Defense Team recorded approximately 225 Written Impact Narratives (WIN) in FY 2019, slightly exceeding the number in FY 2018. A WIN is an organizational metric that showcases ITA's contribution to a company's success. These include ITA and particularly Commercial Service (CS) personnel-impacted deals with small- and medium-sized companies, as well as larger corporations such as Bell Helicopter, Boeing, General Dynamics, Lockheed Martin, and United Technologies Corporation.

The Global Team held over 4,000 counseling sessions with approximately 2,000 U.S. aerospace companies, helping them to resolve international trade issues, identify new export markets, and develop strategies for entering those markets.

The Global Team participated in over 35 domestic and international aerospace trade events at which team members supported the U.S. industry with one-on-one counseling sessions, arranged individualized business-to-business meetings with international business partners, and provided additional export counseling services. ITA trade show support generated hundreds of trade leads for participating companies, allowing them to enter or expand their exports to international markets. These international trade events included the Paris Air Show, the Australian/Avalon Air Show, the MSPO (Poland) Air Show, F-Air (Colombia), Aero India, the International Defence Exhibition and Conference (IDEX), and Japan Aerospace, among others.

Bureau of Industry and Security

During this fiscal year, the Bureau of Industry and Security (BIS) continued to support the U.S. Munitions List/Commerce Control List efforts as they relate to spacecraft. On March 8, 2019, the Departments of State and Commerce published requests for public comments on the spacecraft and related items enumerated and described therein. The feedback received has informed ongoing interagency discussions on streamlining export control regulations for both the U.S. commercial space industry and those of international partners. Consistent with the objectives of Space Policy Directive–2, the Departments of State and Commerce seek to bolster the U.S. commercial space sector by lowering the administrative burden, decreasing regulatory compliance costs, and increasing U.S. exports.

On May 23, 2019, the Bureau of Industry and Security added aircraft specially designed to be air-launch platforms for space-launch vehicles to the Commerce Control List. Covering such platforms under export controls addresses the military utility of the air-launch method, which is increasingly popular in the commercial space community. This change reflects agreements made with international export control partners to place controls on this emerging technology for national security reasons.

Department of the Interior

DOI

Remotely sensed data and derived information contribute substantially to mission-critical work across the Department of the Interior (DOI). This DOI section highlights a sample of DOI remote sensing applications and illustrates a range of technology, platforms, and specialized sensors employed.

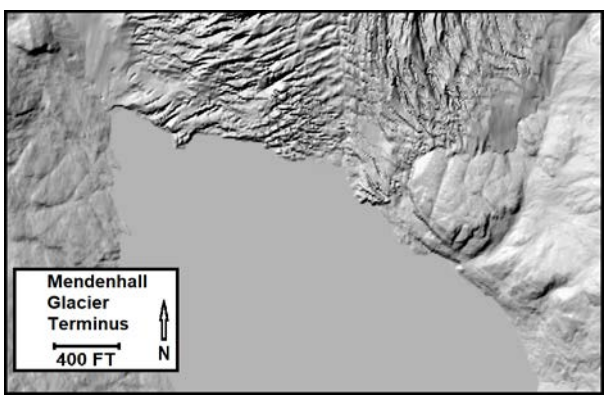
U.S. Geological Survey

The U.S. Geological Survey (USGS) was both a user and a provider of remotely sensed data in 2019. The USGS managed the Landsat satellite series and a web-enabled archive of global Landsat imagery that dates back to 1972. Landsat represents the world's longest continuously acquired collection of spaceborne moderate-resolution land remote sensing data, and the entire archive became available for download at no charge in December 2008. The USGS also distributed aerial photography through the National Map. It archived and distributed historical aerial photography; light detection and ranging (lidar) data; declassified imagery; hyperspectral imagery; data collected by Unmanned Aircraft Systems (UAS); and imagery from a variety of Government, foreign, and commercial satellites. These data were used for a wide variety of applications, such as mineral resource development; monitoring the health of U.S. and global ecosystems; land-use change; emergency response; and assessments of natural hazards such as fires, hurricanes, earthquakes, droughts, and floods.

Alaska Interferometric Synthetic Aperture Radar Elevation Data Status

The USGS coordinated a 3D Elevation Program (3DEP) effort with other Federal agency partners and the State of Alaska to acquire new statewide Alaska elevation data. Under its Geospatial Products and Services Contract (GPSC), the USGS contracted with vendors to acquire 5-meter-resolution elevation data using Interferometric Synthetic Aperture Radar (IfSAR) sensors flown on aircraft. The data products derived from this effort include a Digital Terrain Model (DTM) representing the bare earth, a Digital Surface Model (DSM) representing the tops of vegetation and structures, and an orthorectified radar intensity image (ORI). These new data replace decades-old 60-meter-resolution elevation data that have known vertical and horizontal errors. With the 2019 acquisition of Kodiak, St. Lawrence, St. Matthew, St. Paul, St. George, Chirikof, Middleton, and the western Aleutian Islands, complete statewide IfSAR coverage has been achieved.

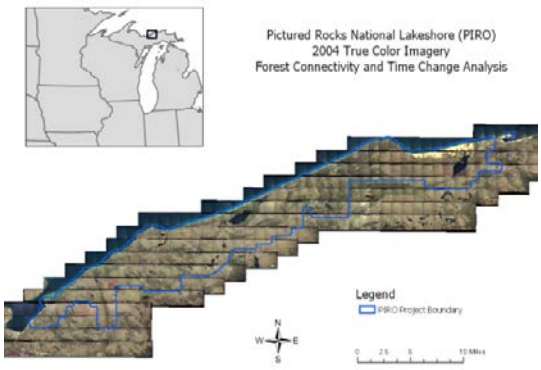
IfSAR data are being used in a wide variety of mapping, resource management, and human safety applications. The new elevation data serve as a foundational layer for new USGS digital topographic maps that are being generated statewide for Alaska. IfSAR data are also being used to update and refine the digital water-surface layer for Alaska that is critical to many applications. These Alaska mapping efforts are coordinated through the Alaska Mapping Executive Committee (AMEC), an executive body cochaired by the Department of the Interior and the Department of Commerce. AMEC members represent multiple Federal agencies and the state.



IfSAR hillshade depiction of the Mendenhall glacier terminus, Alaska.

Deriving Forest Canopy Connectivity and Change Analysis from Aerial Imagery

USGS biologists at the Pictured Rocks National Lakeshore in Michigan's Upper Peninsula are studying how wildlife is reacting to the canopy cover and food availability changes caused by beech bark disease (BBD). This study will provide the Pictured Rocks National Lakeshore biologists with a canopy connectivity layer that shows change over time, allowing them to see where the forest has changed the most.



Pictured Rocks National Lakeshore 2004 true-color imagery showing forest connectivity and time-change analysis.

To create the forest canopy layer, the USGS Upper Midwest Environmental Sciences Center leveraged NASA's Ames Stereo Pipeline and aerial imagery as part of the Natural Resources Preservation Project (NRPP). The Ames Pipeline used a DTM to create DSMs from stereo aerial imagery. Using imagery of the National Lakeshore from different time periods, the DSMs will allow the park to visualize where canopy has been lost and replaced historically. Canopy height models will be derived from the DTM and DSM, and an R script will identify forest canopy connectivity for each time period. A time-change analysis will be conducted between 2005 and the current time to identify areas with the greatest change due to the BBD infestation.

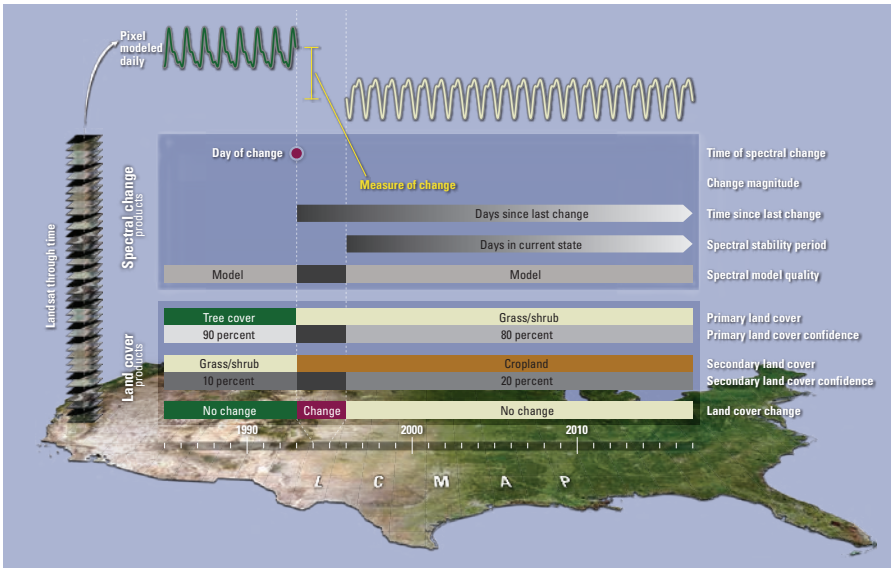
Launching the Continuous Monitoring of U.S. Lands: Land-Change Monitoring, Assessment, and Projection

In 2019, the USGS initiated a capacity to monitor land-surface change across the conterminous United States to meet increasing demands for timely and frequent integrated land-cover and -change information. Land Change Monitoring, Assessment, and Projection (LCMAP) is enabling nationwide tracking and

characterization of annual changes in land cover, use, and condition and will produce in-depth assessments of current and historical land change. The goals of LCMAP include developing a capability to detect and characterize historical land change from data in the 1985–present Landsat archive, producing a suite of validated annual land-change and land-cover maps and area statistics, and ultimately modeling past and future change not covered by the satellite record.

Historical land-surface change and land-cover data are created from all available cloud- and shadow-free pixels in the Landsat Analysis Ready Data (ARD) archive using the Continuous Change Detection and Classification (CCDC) algorithm. CCDC is an automated time-series modeling approach that identifies different change events and characterizes a large variety of land-cover types, uses, and conditions. By using the historical depth of the Landsat archive processed with high geometric fidelity and gridded to a common tiling scheme, LCMAP reveals trajectories of land change from the mid-1980s to the present at 30-meter spatial resolution.

The LCMAP Collection 1 product suite includes 10 annual historical land-change and land-cover map products. The initial release covers a 33-year period



LCMAP produces land-cover change information for every location in the United States for the Landsat 4 through Landsat 8 record. Analysis Ready Data, coupled with the Continuous Change Detection and Classification algorithm, provide models for every location based on the spectral and temporal properties of the land surface. The five spectral change products and five land-cover products listed on the right are derived from these model results.

from 1985 to 2017, with more recent years to follow. Sample products are now available for a single tile over central California, and the national production is in progress. LCMAP products' accuracy was assessed using an independent reference dataset including land-cover observations for each year from 1984 to 2018 at 25,000 randomly selected sample sites across the United States. A national accuracy assessment report for LCMAP monitoring products will be produced from these data.

Mapping Long-Term Landscape Dynamics in the Kenai Peninsula, Alaska

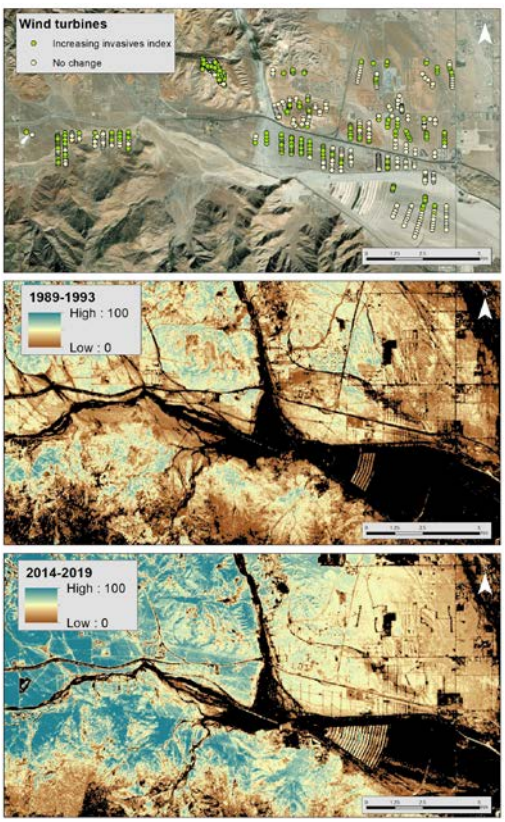
Spruce bark beetle outbreaks, natural and human-caused wildfires, shrub expansion, lake drying, permafrost thaw, and industrial activities have all contributed to extensive land-cover change across the peninsula. Detecting, mapping, and tracking the cumulative effects of these disturbances are important for state and Federal resource management agencies.

USGS researchers are developing a Landsat-based time series of spatially explicit vegetation maps that are better suited to capturing the extent and magnitude of various and prominent land-cover changes that have occurred across the Kenai Peninsula over the last 40 years and more. This study aims to develop a simplified and consistent series of spatially explicit vegetation and land-cover types estimated from Landsat legacy imagery across the Kenai Peninsula between 1973 and 2017. While the main focus is on forest and non-forest, land-cover types include needleleaf, broadleaf, and mixed-species forests. Non-forest cover types include shrubs, upland and wetland graminoid, alpine, barren, and water. A time series composed of these classifications allows for the detection and quantification of forest losses, growth, and transitions as well as other major changes, such as wetland loss due to drying and woody vegetation encroachment. This work provides a new record of landscape change and better quantifies how disturbance events and natural succession have shaped the distribution of vegetation types across the peninsula, an important resource for local, state, and Federal land managers tasked with monitoring and managing natural resources across the Alaskan peninsula.

Monitoring Exotic Annual Grasses Around Energy Development Sites with Landsat Time Series

Once established, exotic annual plants like red brome (*Bromus rubens*) and cheatgrass (*Bromus tectorum*) can rapidly alter community composition and increase wildfire risk. Red brome and cheatgrass become green earlier than native vegetation, producing a distinct "pulse" of greenness in the early spring. This pulse can be exploited to identify the location of these annual plants by using the difference between a spring satellite image with peak cheatgrass greenness and an early summer image where cheatgrass is dormant. Using these approaches, researchers are developing annual Landsat time series to analyze trends and patterns of early-season invasive grasses around disturbed wind turbine sites as well as mapping invasive trends across the entire Mojave Desert of southern California.

The team used a cloud-based approach to analyze Landsat imagery from 1985 to 2018 and develop estimates of invasive grasses surrounding 1,755 wind turbines installed between 1988 and 2013. An annual invasive species index was developed that uses the contrast in early-season and late-season Normalized Difference Vegetation Index (NDVI) to estimate the relative amounts of invasive annual plants each year at turbine and



The top image shows the difference in early-season invasives index values before and after turbine construction compared to surrounding control areas. Green indicates turbines with higher index values in the period after construction, and yellow indicates no change or lower invasive index values after construction. The five-year average early-season invasives index values for 1989–93 (middle) and 2014–18 (bottom) illustrate trends across the larger landscape. Green values indicate persistent yearly high NDVI values over each period (greater than 0.2).

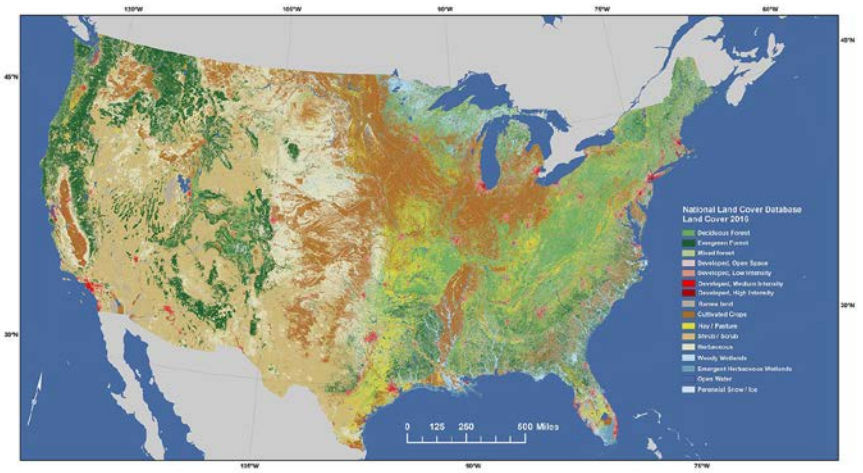
control sites. The maximum greenness, as indicated by NDVI, was used for the early season (January through June), and median greenness for the later dry season (July through October).

The results showed an increase in early-season invasive species after turbines were installed, but also a similar increase over time in some surrounding control areas. Maps of the invasive index show a region-wide increase during the study period. Much of the regional increase occurred near the wind development sites, but the extent to which the disturbance caused by energy development contributed to the spread of invasive species across the greater landscape is unknown, considering the possible role of confounding land use and climatic factors on invasive spread.

Advances in cloud computing allow rapid calculation of dense time series of NDVI and other spectral indices. These methods show promise for helping land managers identify and map other annuals and exotic weeds that have a less predictable phenological signal but respond to individual precipitation events or summer precipitation.

National Land Cover Database 2016 Completed and Released

In 2019, the USGS completed and released the National Land Cover Database (NLCD) 2016 for the United States. NLCD 2016 documents land cover in the conterminous (lower 48) United States from 2001 to 2016. The database includes seven layers that portray the Nation's land cover for the years 2001, 2004, 2006, 2008, 2011, 2013, and 2016, as well as four products on urban impervious surfaces for the years 2001, 2006, 2011, and 2016. The NLCD 2016 is fundamentally based on the analysis of Landsat imagery with an emphasis on year-to-year consistency that enables the accurate measurement of change in land cover and impervious surface. The NLCD 2016 provides the ability to understand both current and historical land cover and land-cover change while also enabling monitoring and trend assessments. Data downloads and links to Web Mapping Services are available at the Multi-Resolution Land Characteristics Consortium website, *https://www.mrlc.gov*.



NLCD land cover for 2016, which is the most recent land-cover product available at 30-meter resolution within a consistent, integrated database dating back to 2001 (released in 2019).

Post-Contamination Restoration Monitoring Using Unmanned Aircraft Systems

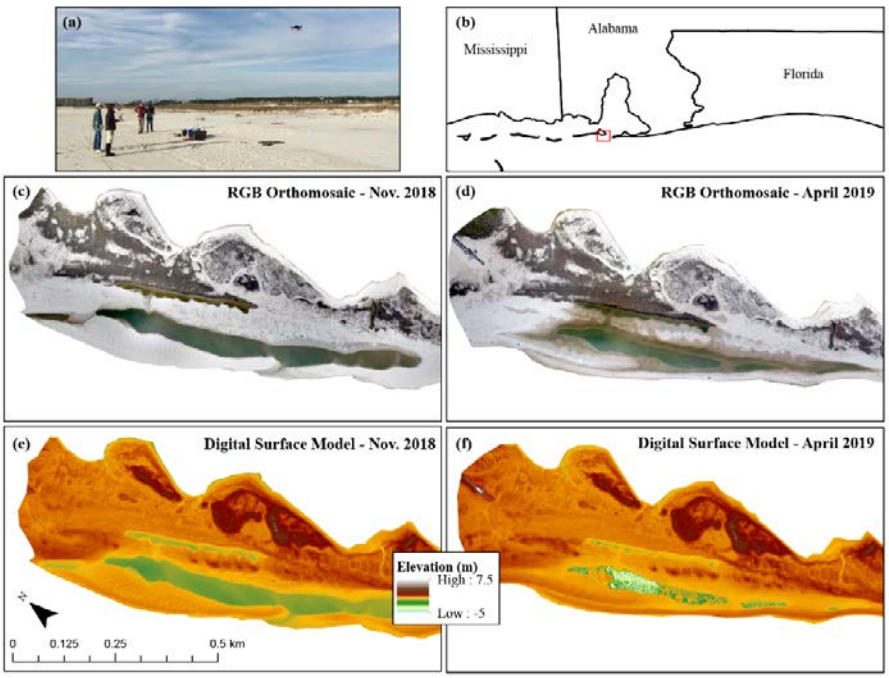
Imagery collected using Unmanned Aircraft Systems (UAS) are used to document baseline vegetation conditions and to monitor the progress of bottomland forest restoration at the Little Saint Francis River Chat Pile (LSFR) site. Structure-from-motion (SfM) photogrammetry are used to monitor the survival and growth of planted woody stems in the bottomland forest restoration and to monitor the effectiveness of invasive species eradication efforts throughout the site. Measurements captured by UAS imagery and derived elevation products include overall and species-level survival rate, growth between UAS sample images, and variation in plant species condition between UAS sampling events. The efficiency and effectiveness of data derived from UAS imagery will be compared to that of field-collected data to identify appropriate applications of UAS technology.

Imagery from UAS is used to assess and monitor the progress of a small bottomland forest restoration and invasive plant species eradication efforts at a former mining site along the Little Saint Francis River in southeastern Missouri.

Shorebird Habitat Usage, Change on Gulf Barrier Islands

Migratory species depend on a chain of habitats for survival, including breeding habitats, overwintering sites, and migratory stopover locations. Barrier islands in the northern Gulf of Mexico provide habitat for all three of these life-history phases and are important habitat for many shorebird species, such as red knots, piping plovers, and western sandpipers. Natural resource managers require tools for predicting how an island's characteristics and a species's use of an available habitat may change over time and under varying management scenarios.

As part of the Coastal Resource Evaluation for Management Application (CREMA) project, scientists from the USGS St. Petersburg Coastal and Marine Science Center and the Wetlands Aquatic Research Center investigated how barrier island habitats were used by shorebirds and how those habitats changed on Pelican and Little Dauphin Islands, Alabama, over a single winter.



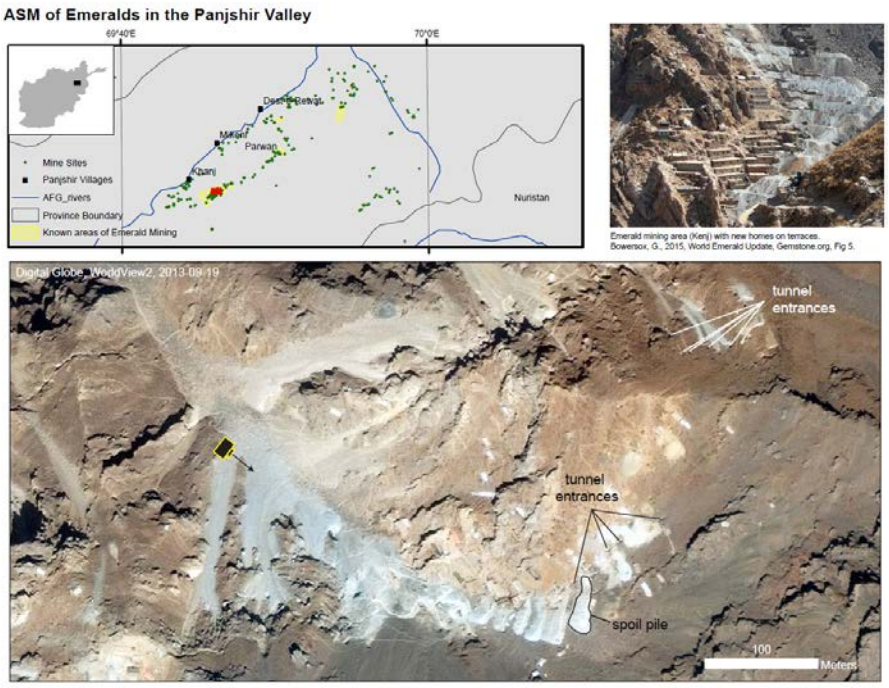
(a) USGS scientists fly a UAS over (b) Pelican Island, Alabama, to collect data used to derive (c–d) natural-color ortho-mosaics and (e–f) digital surface models. UAS flights were repeated monthly from September 2018 through April 2019 in order to investigate how landscape features and shorebird wintering habitat availability change through time over a single winter. Note: Elevations over water do not accurately represent water depth.

For this effort, monthly surveys were conducted using a UAS from September 2018 through April 2019 to derive centimeter-level natural-color and multispectral ortho-mosaics as well as digital surface models using SfM photography. In addition to UAS efforts, scientists conducted extensive vegetation and elevation surveys using a Real-Time Kinematic Global Positional System (RTK GPS) for training and validation. These data are being used to develop probabilistic maps of water levels on barrier islands and to produce bare-earth digital elevation models from the SfM products. The lidar data and derivatives are coupled with field data, tide data, and high-resolution orthophotography within a geomorphology-based mapping framework to produce a time series of maps of barrier island habitats (e.g., intertidal habitats, beach, and dune). The mapping framework uses a rule-based, geographic object–based image analysis approach and applies Monte Carlo analyses for the treatment of elevation uncertainty for elevation-dependent habitats. Finally, the team is conducting monthly shorebird surveys to document bird behaviors and habitat use.

These products will be combined with other ecogeomorphic variables at multiple scales, such as distance from shoreline and vegetation cover, in a probabilistic model that relates shorebird habitat usage with landscape characteristics. This project aims to provide natural-resource managers with tools needed to protect sensitive coastal ecosystems despite uncertainty in future conditions.

Special Geologic Studies: Artisanal and Small-Scale Mining of Conflict Minerals

This project, led by the USGS Florence Bascom Geoscience Center, focuses on the illegal artisanal and small-scale mining (ASM) of small and low-grade mineral and gemstone deposits. Project scientists employ field mapping, geomorphological techniques, and remote sensing to map, monitor, and evaluate mineral deposits and ASM activities in conflict zones and during complex emergencies. The research is directly applied to addressing issues of international peace and security, terrorism and conflict financing, money laundering, trans-boundary material flows, and human and environmental health degradation.

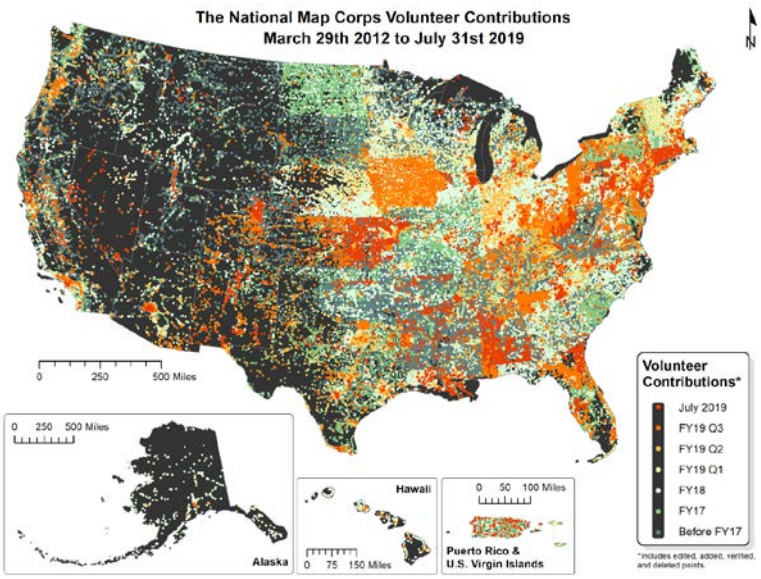


Satellite image mapping and monitoring of small-scale emerald mining in the Panjshir Valley, Afghanistan.

Using Imagery to Crowdsource The National Map

The National Map Corps (TNMCorps), a crowdsourced mapping project, relies on volunteers to assist the USGS National Geospatial Program by collecting and editing humanmade structures data for The National Map. Through their participation, volunteers make important contributions to the USGS's ability to provide the Nation with accurate mapping information.

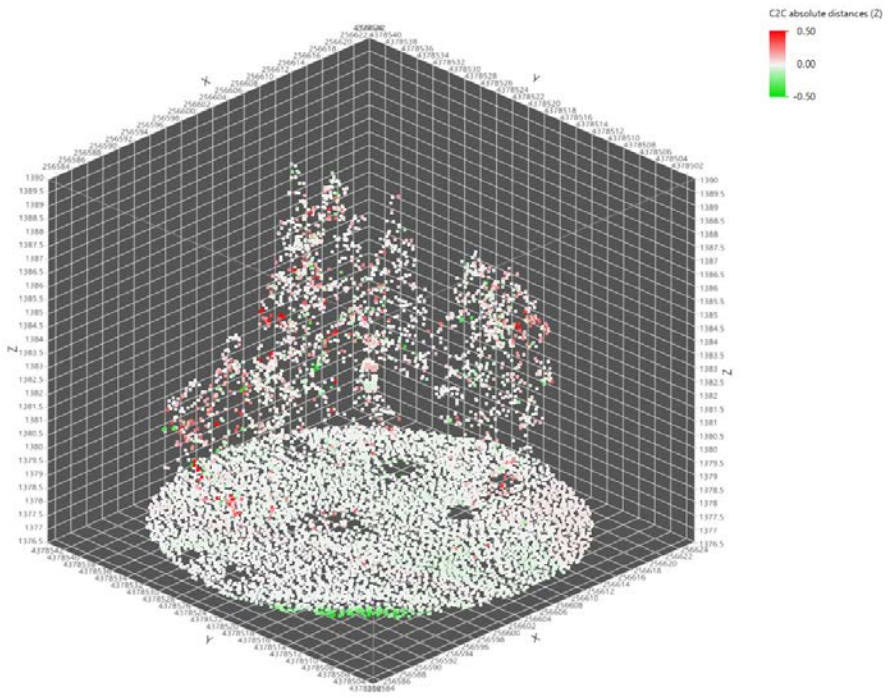
Volunteers collect and update different structure feature types in all 50 states, as well as in Puerto Rico and the U.S. Virgin Islands. The structure feature types include schools, colleges and universities, fire and emergency management stations, law enforcement, prisons and correctional facilities, hospitals, ambulance services, cemeteries, post offices, courthouses, and city/town halls. Through a tiered-editing approach, volunteers improve the structures data by adding new features, removing obsolete points, and correcting existing data. The updates are then incorporated into The National Map and ultimately into U.S. Topo maps. As of July 2019, more than 1,800 users have made over 546,000 edits to over 433,000 unique points.



USGS TNMCorps volunteer contributions from March 29, 2012, to July 31, 2019. Each point on the map represents a single volunteer-edited structure feature. These volunteer contributions include edited, added, verified, and deleted points.

Using Terrestrial Laser Scanning Data to Validate 3DEP

To validate the quality of light detection and ranging (lidar) data collected for the 3D Elevation Program (3DEP), the USGS uses methods detailed in "Accuracy Standards for Digital Geospatial Data" developed by the American Society for Photogrammetry and Remote Sensing (ASPRS). These methods involve using survey-grade global positioning system (GPS) checkpoints for validation on the bare-earth surface distributed throughout the project site in flat open areas and under vegetation. While this method is sufficient for evaluating the bare-earth digital elevation models (DEMs), it is inadequate to understand the quality of the lidar point cloud data for points above the ground, such as for vegetation and buildings. As a result, the end user may incorrectly assume that the root mean square error (RMSE) derived for the bare-earth DEM applies to every lidar point in the dataset. This pilot project used survey-grade terrestrial laser scanning (TLS) data to compare and assess all lidar points collected for 3DEP in plots spread throughout several projects. Initial findings show that having more TLS scans available as "ground truth" information for 3DEP improves the understanding of 3DEP data accuracy and measurement uncertainties.



This sample graphic shows Z differences between terrestrial laser scanning (TLS) and 3DEP data for single plot. Points colored white are 3DEP points that are very close in the vertical dimension to ground-based lidar points. Knowing vertical differences between 3DEP lidar and "ground truth" TLS scans help end users better understand the amount of uncertainty in the 3DEP measurements and identify any potential calibration issues.

Wolf Population Monitoring Using Noninvasive Aerial Telemetry Methods

To evaluate the health and status of wolf populations in east-central Superior National Forest (SNF) of northeastern Minnesota, the USGS Northern Prairie Wildlife Research Center monitors their movements and population dynamics. Since 1968, researchers have used Very High Frequency (VHF) and/or Global Positioning System (GPS) radio collars to locate and monitor individual wolves. During winter, the collars are located by aerial tracking, which allows observation of collared wolves and their packs, thus providing data for annual surveys of populations and long-term population trajectories. However, noninvasive methods are preferred over physically capturing animals to radio-collar them. The USGS, in cooperation with the Minnesota Department of Natural Resources, tested the utility of a suite of noninvasive methods to monitor the wolf population in the SNF while using traditional aerial radiotelemetry results for comparison.

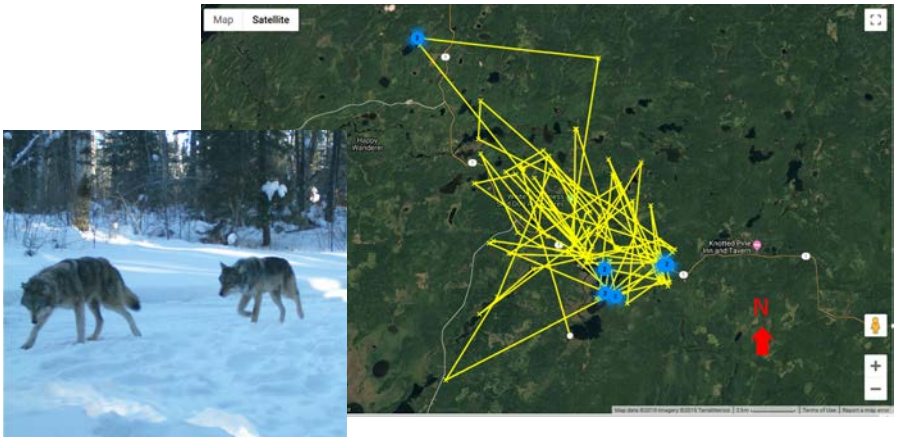


Photo: GPS-collared Wolf 7248 following his packmate, captured on a trail camera during winter 2019.
Map: GPS-collared Wolf 7248's movements during winter 2018.

Recent advances in noninvasive methods, such as genetic surveys and camera trapping, combined with ground and aerial observations of tracks in the snow, may now provide reasonably accurate population estimates. Information on wolf pack size and territory obtained from snow tracks, camera trapping, genetic analysis of scats, and citizen-scientist observations was compared with aerial observations of radioed wolves and their packmates. The first planned January–March 2019 test was shortened due to the Federal Government shutdown. However, results were encouraging enough that the methods will be tried again during winter 2020. Preliminary conclusions suggest that noninvasive methods reduce reliance on trapping wolves for radio-collaring, although they may or may not entirely replace radio-collaring, depending on research questions.

Bureau of Land Management

The Bureau of Land Management (BLM) leverages ground, air, and spaceborne remote sensing technologies to support its mission to sustain the health, diversity, and productivity of public lands for the use and enjoyment of present and future generations. These technologies include aerial and close-range photography; multispectral, hyperspectral, and thermal infrared camera/imaging systems; and radar and light detection and ranging (lidar). The BLM also utilizes passive and active imaging system information collected by Unmanned Aircraft Systems (UAS). Remote sensing data and products are being used to address a host of BLM

monitoring requirements, including energy development, mine production verification, assessment of land-cover condition through time, and wildfire response and mitigation. Finally, the BLM requires field-based measurements to support management decisions covering vast expanses of land. By integrating remote sensing into the BLM's Assessment, Inventory, and Monitoring strategy, the bureau uses field-based data to generate information and maps that would otherwise be too expensive to produce. The BLM is leveraging remote sensing to provide an integrated, quantitative monitoring approach to efficiently and effectively document the impacts from authorized and unauthorized disturbance and land-treatment activities at local and regional scales.

Avalanche Debris Flow Monitoring and Structural Imaging

Above-average snowpack across Colorado in 2018–19 led to an unprecedented avalanche season, with the concomitant deposition of debris in streams creating flooding hazards across the state. This was especially true for Lake City in Hinsdale County, sitting at the confluence of Henson Creek and the Lake Fork of the Gunnison River, which together had more than 30 avalanches upstream of town. Compounding the threat to Lake City is the presence of two historic, unmaintained dams on Henson Creek built in the late 1800s. While both dams had been partially breached to ease flooding concerns in the past, emergency managers were concerned that the sheer quantity of debris in the streams could plug the breaches in each dam, filling the historic reservoirs with snowmelt.

The BLM National Operations Center (NOC) assisted the Gunnison Field Office and the State of Colorado with emergency mapping and analysis to 1) quantify the capacity of the upstream reservoirs should the historic dams become clogged, 2) document structures that would be threatened by flooding, and 3) provide timely catchment-wide imagery to monitor snowmelt. Given the need for both ultra-fine resolution and broad-scale remotely sensed products, the NOC leveraged UAS and multiple satellite imaging systems to accomplish these objectives.

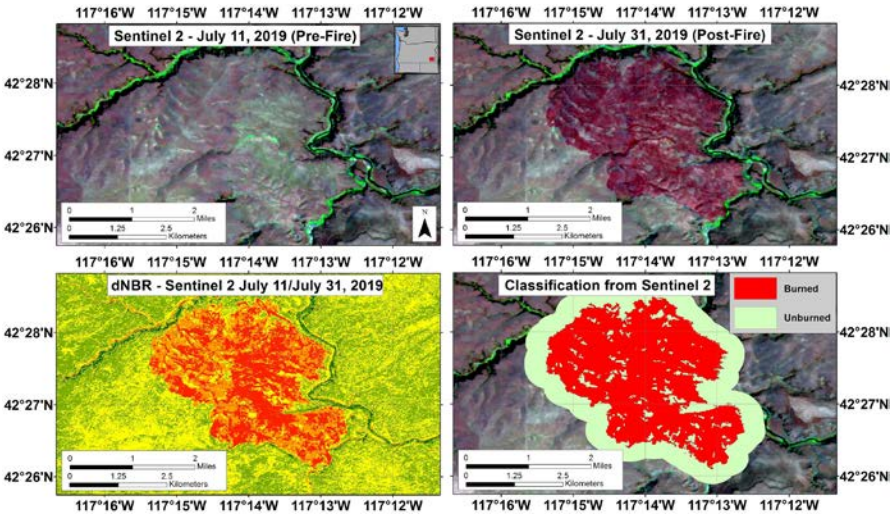
Within two weeks of initial contact, UAS pilots from the NOC and the USGS National UAS Office traveled to Lake City, conducting nearly 20 imagery and video acquisition flights over two days. By week's end, the NOC team had created

1) Textured mesh of Ute Ulay Dam, 2) point cloud of water tower, and 3) areal extent of historic reservoir.

a 2.5-centimeter-resolution base map and estimate of reservoir extent and capacity. Additional processing generated aesthetically pleasing three-dimensional models of important structures that will serve as a historical record should they be damaged by flooding. Sentinel-2 and WorldView-2 and -3 satellite imagery was used to provide multi-scale, multitemporal environmental monitoring of the greater area. Taken together, these data allowed the BLM field office staff and state emergency managers to make more informed decisions regarding mitigation efforts.

Emergency Stabilization and Rehabilitation Postfire Imagery Support

Since 2014, the National Operations Center (NOC) has provided remotely sensed geospatial data products to support management officials conducting Emergency Stabilization and Rehabilitation (ESR) activities on wildfire-affected BLM lands. The ESR program is implemented to lessen postfire effects, such as erosion, and to restore affected habitats. Remote sensing products assist management officials in monitoring vegetation treatments and reforestation, as well as rehabilitating land cover. To support 2019 ESR efforts, the NOC provided products



Sentinel-2 products derived in response to the Drummond Basin Fire in Oregon (from left to right): prefire multispectral image, postfire multispectral image, dNBR from pre- and postfire NBRs, and a vector classification identifying burned and unburned cover.

derived from the European Space Agency's Sentinel-2 satellites to requesting officials. The products included pre- and post-event Sentinel-2 visible to shortwave-infrared (VSWIR) imagery, which have been spatially subset to the fire-affected area to reduce file storage space. Normalized Difference Vegetation Index (NDVI), Normalized Burn Ratio (NBR), Delta NDVI (dNDVI), Delta NBR (dNBR), and fire-retardant location products are also disseminated to meet ESR objectives. In addition, the NOC provided a classification product identifying burned and unburned cover.

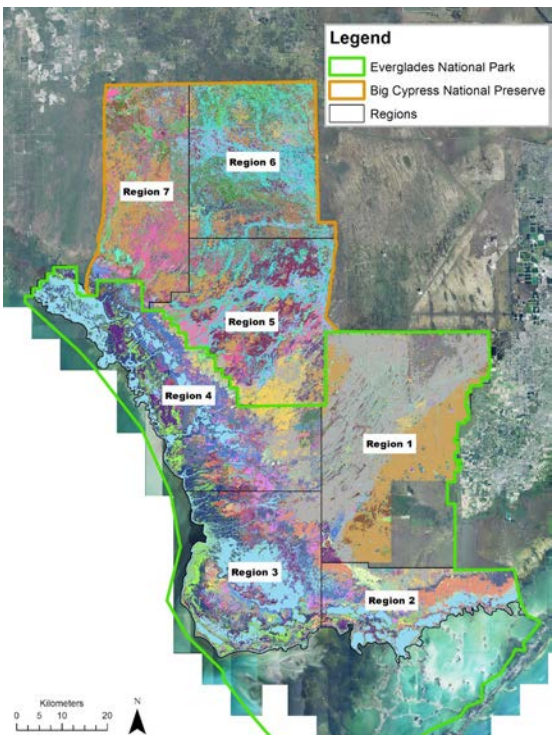
National Park Service

The National Park Service (NPS) has a substantial investment in and a long history of using aerial and spaceborne remote sensing and GPS technologies. The NPS Inventory and Monitoring Program conducts baseline inventories for more than 270 parks across the Nation. Remote sensing data are a critical source of information regarding geology, soils, vegetation, and infrastructure. NPS utilized aerial photography and satellite imagery to compile vegetation maps—a monumental task, given that the agency has responsibility for over 30 million acres. These data are particularly critical for NPS activities in Alaska because of its remote

and vast expanses of public land and the fact that the Arctic is warming rapidly in response to climate change. The NPS took advantage of the open and freely available Landsat archive to quantify decadal changes in glacier ice cover and document land-cover change in national park units. The NPS has been DOI's sponsoring agency to map all large wildland and prescribed fires as part of the DOI Monitoring Trends in Burn Severity project, using the Landsat archive. GPS supported field data collection, navigation, and search-and-rescue operations conducted by the agency.

The Vegetation-Mapping Project of Everglades National Park and Big Cypress National Preserve

The Everglades National Park (EVER) and Big Cypress National Preserve (BICY) vegetation-mapping project is part of the Comprehensive Everglades Restoration Plan (CERP). The CERP is a cooperative effort between the South Florida Water Management District (SFWMD), the U.S. Army Corps of Engineers (USACE), and the National Park Service (NPS) Vegetation Mapping Inventory (VMI) Program. The goal of this project is to produce a spatially and thematically accurate vegetation map of these two park units prior to the completion of restoration efforts for use in management, research, and monitoring.



Footprint of the Everglades National Park and Big Cypress National Preserve vegetation-mapping project showing mapping regions and completed areas. The project covers an area of approximately 7,400 square kilometers (1.84 million acres).

The project is near completion. The project covers an

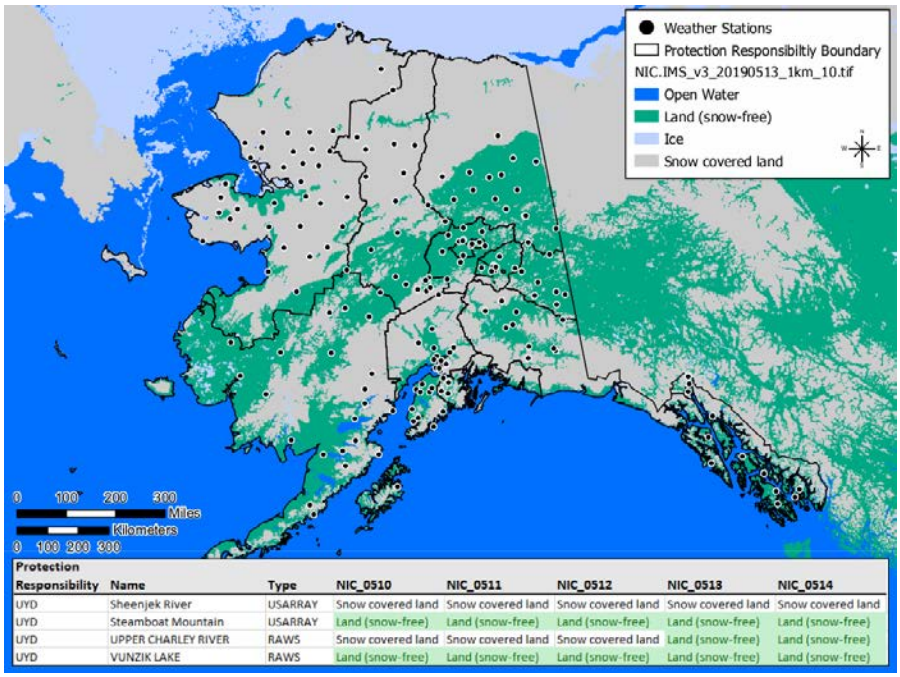
area of approximately 7,400 square kilometers (1.84 million acres) and consists of seven mapping regions: four regions in EVER (Regions 1 through 4) and three regions in BICY (Regions 5 through 7). Photo-interpretation is performed by superimposing a 50-meter × 50-meter (¼-hectare) grid cell vector matrix over stereoscopic color infrared aerial imagery on a digital photogrammetric workstation. Photo-interpreters identify the dominant vegetation community in each cell by applying majority rule algorithms, recognizing characteristic community-specific spectral signatures, and referencing an extensive ground-truth database.

All regions have been mapped except for a portion of Region 1. Thematic accuracies of completed regions range from 85 percent to 93.1 percent, while lower 90th percentile confidence intervals range from 82 percent to 90.8 percent. Region 2 and Region 3 are available for download from the NPS Integrated Resource Management Applications (IRMA) portal at *https://irma.nps.gov/DataStore/Reference/Profile/2244641* and *https://irma.nps.gov/DataStore/Reference/Profile/2257752*, respectively. The map for eastern Big Cypress (Regions 5 and 6) was completed in 2019 and will be available on IRMA by 2020. The Region 4 vegetation map is pending quality assurance and quality control (QAQC), evaluation and the Region 7 vegetation map is pending peer review.

Tracking Snowmelt and the Onset of Wildfire Season in Alaska

A part of Alaska's boreal forest burns every summer. To predict which areas are most susceptible to wildfire, managers use weather data collected at remote stations to assess fuel dryness and burnability. Managers must start gathering these data within just a few days after the snow has melted away from a weather station in the spring. But snow melts unevenly. Aspect, elevation, and weather all influence the pattern and speed at which snow melts. Land managers thus face a challenge: how to monitor the melting of the snow in detail across a huge region that is topographically complex and only sparsely populated. Such monitoring has previously been accomplished subjectively from aircraft.

This study pairs subjective airborne assessments with objective assessments of snowmelt captured remotely by various satellites. Using data from the Interactive Multisensor Snow and Ice Mapping System (IMS), the Alaska wildland fire



Protection Responsibility	Name	Type	NIC_0510	NIC_0511	NIC_0512	NIC_0513	NIC_0514
UYD	Sheenjek River	USARRAY	Snow covered land	Snow covered land	Snow covered land	Snow covered land	Snow covered land
UYD	Steamboat Mountain	USARRAY	Land (snow-free)	Land (snow-free)	Land (snow-free)	Land (snow-free)	Land (snow-free)
UYD	UPPER CHARLEY RIVER	RAWS	Snow covered land	Snow covered land	Snow covered land	Land (snow-free)	Land (snow-free)
UYD	VUNZIK LAKE	RAWS	Land (snow-free)	Land (snow-free)	Land (snow-free)	Land (snow-free)	Land (snow-free)

Sample IMS grid at 1-kilometer spatial resolution. Green pixels represent snow-free ground, while gray pixels indicate remaining snowpack. The tabular data at the bottom of the image indicate the presence or absence of snow at specific points where weather stations are located. For example, the Upper Charley River Remote Automated Weather Station (RAWS) was surrounded by snow-covered ground until May 13.

community can track the changes in snow cover near individual weather stations and across broader spatial scales. Data from IMS were combined with point data representing the location of remote weather stations to produce a continuous, rolling summary of snow and ice conditions. In turn, this information was used to inform decisions on when to start calculating fire weather indices.

Use of these data was first applied in Alaska midway through the melting process in the spring of 2019.

U.S. Fish and Wildlife Service

The U.S. Fish and Wildlife Service (FWS), in concert with its international, Federal, Tribal, state, local, and nongovernmental organization (NGO) partners, used a large number of remote sensing technologies to find optimal solutions to monitor and manage fish and wildlife populations, habitats, waters, wetlands, and landscapes. The FWS utilized acoustic geographic positioning systems (GPS) and

radio telemetry sensors on fish and wildlife for time and location information tied to a variety of remote sensing image products such as aerial and satellite optical imagery, as well as thermal, radar, sonar, and lidar imagery. This time and geospatial system of imagery and location is used to map habitats, find invasive plants, determine flight paths of birds and bats, conduct fish and wildlife inventories, watch over refuge lands, and monitor trust species.

Early-Detection, Rapid-Response Treatment of Cheatgrass

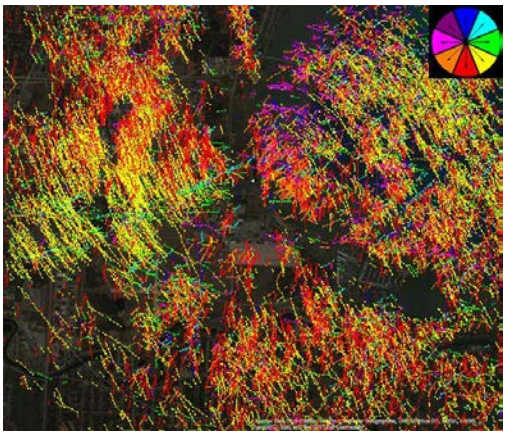
Cheatgrass (*Bromus tectorum*) is a highly invasive, non-native grass that threatens wildlife habitat, migratory corridors, and agricultural production in the sagebrush ecosystems of the western United States. Furthermore, it creates an increased risk of wildfire that threatens infrastructure and human safety. Once an area becomes heavily invaded by cheatgrass, restoration to a native state is difficult and expensive. Early-detection, rapid-response herbicide treatments are an effective way to manage cheatgrass when infestations are small, but they require the ability to detect small patches of cheatgrass across vast acreages.

The FWS Region 6 Division of Scientific Resources worked with remote sensing researchers at the University of Montana to use high-resolution multispectral imagery from the WorldView satellites to map cheatgrass on Red Rock Lakes National Wildlife Refuge and other areas within the Centennial Valley of Montana. This is part of an early-detection, rapid-response management effort being carried out by multiple Federal and state agencies, NGOs, and private landowners.

Studying Great Lakes Migration with Radar and Acoustics

During 2019, the Avian Radar Project surveyed the migration of birds and bats in the Detroit, Michigan, area using mobile avian radar units. Sites located on Lake St. Clair and Western Lake Erie assessed how migrants moved when approaching and leaving urban areas. The mobile avian radar units can track thousands of individual birds or bats simultaneously within about a three-mile range and do so passively, with no need for tagging the animals.

Migration was strong throughout the month of September and included sporadic movements through the beginning of November. These timeframes are in line with what has been observed around the rest of the Great Lakes. Interestingly, many effects witnessed on the main Great Lakes were also observed on Lake St. Clair, including dawn movement toward shore where migrants come in off the water to look for safety amongst the shoreline habitat. In addition to the radar units, researchers deployed ultrasonic microphones near the radar sites and on the Detroit River National Wildlife Refuge property to sample bat activity. These monitors allow researchers to home in on bat activity itself and track the activity levels of the different bat species.



One hour of migration activity near Lake St. Clair. Each line represents one bird or bat that was tracked, and they are colored by their direction of movement.

Data gathered this season will be combined with that from prior years to produce a regional map of migration for the Great Lakes. This map will highlight high-usage areas and help land managers prioritize conservation efforts on areas with the highest importance to migrating birds and bats. Once this map has been developed, it will be combined with data from other sources, including acoustic monitors, to develop a Decision Support Tool that can be used directly by land managers, planners, and policy makers. This tool and the raw data from this and other seasons of the project will be available on the project's website: *https://www.fws.gov/radar/*.

Bureau of Ocean Energy Management

The Bureau of Ocean Energy Management's (BOEM) Environmental Studies Program (ESP) develops, funds, and manages rigorous scientific research specifically to inform policy decisions on the development of energy and mineral resources on the U.S. Outer Continental Shelf (OCS). BOEM uses remote sensing to inform

its research, which covers physical oceanography, atmospheric sciences, biology, protected species, social sciences and economics, submerged cultural resources, and environmental fates and effects. Mandated by Section 20 of the Outer Continental Shelf Lands Act, the ESP is an indispensable requirement informing BOEM's decisions on offshore oil and gas, offshore renewable energy, and the marine minerals program for coastal restoration. Through its ESP, BOEM has provided over $1 billion for research to this end since its inception in 1973.

Atlantic Marine Assessment Program for Protected Species II

The Atlantic Marine Assessment Program for Protected Species (AMAPPS) II is the continuation of a study to assess the abundance, distribution, ecology, and behavior of marine mammals, sea turtles, and seabirds throughout the U.S. Atlantic Outer Continental Shelf (OCS). AMAPPS II represents a collaboration between BOEM, the National Oceanic and Atmospheric Administration (NOAA), the U.S. Fish and Wildlife Service (FWS), and the U.S. Navy. Broadly, the goals of AMAPPS II are to place the creatures listed above in an ecosystem context and to provide spatially explicit density estimates in a format that can be used when making marine resource management decisions. Achieving these objectives will provide to managers enhanced data that are essential to supporting conservation initiatives mandated under the National Environmental Policy Act (NEPA), Marine Mammal Protection Act (MMPA), Migratory Bird Treaty Act (MBTA), and Endangered Species Act (ESA).

Satellite-tagged weaned gray seal pup (*Halichoerus grypus grypus*). (Photo credit: Sophie Whoriskey, Mystic Aquarium, authorized via NOAA Northeast Fisheries Science Center [NEFSC] to conduct seal research activities during the study under Permit No. 17670-02 issued to the NEFSC by the National Marine Fisheries Service [NMFS] Office of Protected Resources and U.S. Fish and Wildlife Service Special Use Permit #53514-130003).

Because marine ecosystems are complex and involve dynamic assemblages of many coexisting species, a suite of data collection and analytical techniques are being used to understand these marine ecosystem processes and achieve the AMAPPS II's objectives. To enumerate

distribution and abundance, the following types of data are collected: visual sightings of cetaceans, seabirds, sea turtles, and seals from shipboard and aerial surveys; acoustic detections of vocalizing cetaceans and fish from ship-towed and bottom-mounted passive acoustic recorders; and location/depth information telemetered to satellites from radio tags affixed to turtles, seals, and cetaceans.

More information about the status of AMAPPS II can be found on BOEM's website and from NOAA at *https://www.nefsc.noaa.gov/psb/AMAPPS/*.

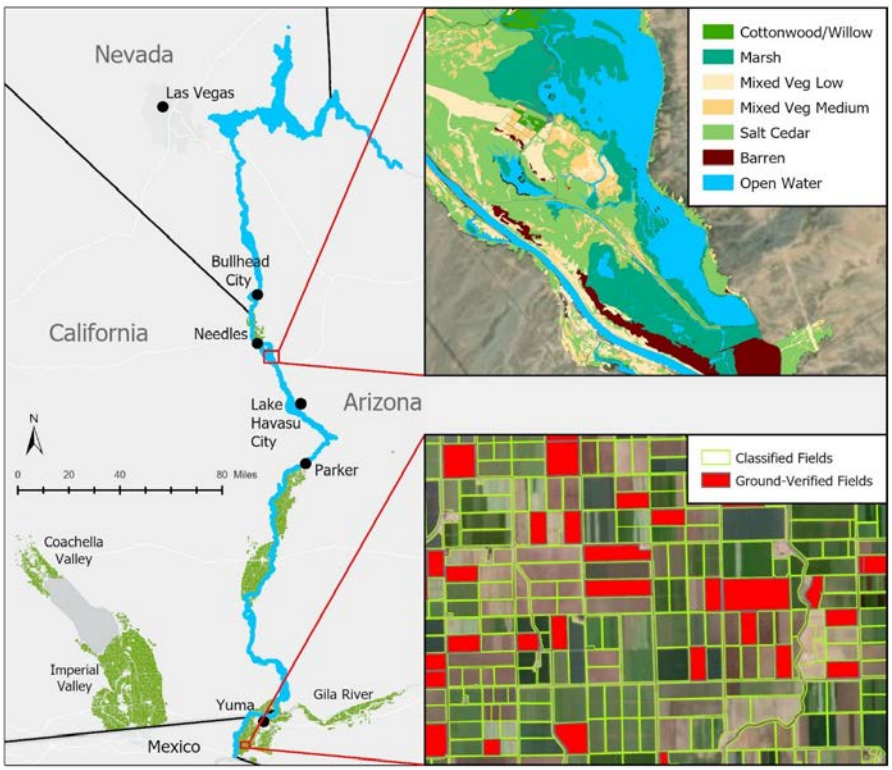
U.S. Bureau of Reclamation

The Bureau of Reclamation (BOR) uses Landsat data to help monitor consumptive water use throughout the western United States. BOR analysts use Landsat imagery to map irrigated crops for estimating water demand and to monitor interstate and inter-basin water compact compliance. The BOR is also involved in ecological restoration of a number of rivers in the West. Light detection and ranging (lidar), multispectral aerial imagery, and sonar data are used to generate maps of topography, vegetation, and river channel bathymetry, which help guide restoration activities.

Estimates of Evapotranspiration and Evaporation Along the Lower Colorado River

The Colorado River is the principal source of water for agriculture and riparian vegetation in Arizona, southern California, and southern Nevada. The BOR Lower Colorado Region accounts for water use in each state, verifies water conservation programs, and fulfills other water management information needs in the Lower Colorado Basin. To accomplish this, BOR monitors more than 3.5 million acres of agricultural land and riparian vegetation along the Lower Colorado River, from Hoover Dam south to the international border with Mexico.

Four times per year, BOR performs supervised classifications on every field along the main stem Colorado River and the Imperial and Coachella Valleys, and along the Gila River. This is accomplished using a combination of multispectral satellite data, aerial images, and ground-based field verifications. Roughly half of the



The BOR uses remote sensing and geographic information system (GIS) data to map agricultural fields, riparian vegetation, and open water in order to estimate evapotranspiration and evaporation within the Lower Colorado Region (left). Examples of the riparian/open water databases near the Havasu National Wildlife Refuge, Arizona (top right), and the agricultural database near Yuma, Arizona (lower right).

collected verified fields are used to train the satellite imagery and determine the crop growing on each field for each time period. The other half of verified field data are used to assess the accuracy of each classification. Subsequently, data about the crop type and acreage along with evapotranspiration (ET) crop coefficients are used to estimate the evapotranspiration from crops within each area.

BOR also maintains riparian vegetation and open water datasets to determine evapotranspiration and evaporation from these sources. Each year, these datasets are updated using the best possible imagery (satellite or aerial) by performing change detection analyses. Results from these efforts are reported annually in the report *Lower Colorado River Annual Summary of Evapotranspiration and Evaporation*.

This information assists the BOR in meeting its U.S. Supreme Court mandate to provide detailed and accurate records of diversions, return flows, and consumptive use estimates of water diverted from the mainstem of the Lower Colorado River.

This program is an example of implementing remote sensing–based methodologies to meet the BOR's water management needs.

Disclaimer: Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Federal Communications Commission

FCC

The Federal Communications Commission (FCC) formulates rules to facilitate the provision of commercial satellite services in the United States. It also issues licenses for the deployment and operation of all nongovernmental U.S. satellites. Internationally, the FCC coordinates satellite radio frequency usage with other countries. The FCC's activities in FY 2019 related primarily to commercial communications satellites and Earth observation satellites, as well as experimental satellites.

The FCC took a number of significant actions in administrative and rulemaking proceedings in FY 2019, among these:

- On November 15, 2018, the FCC partially granted a request by the European Commission for waiver of the FCC rules in order to permit non-Federal devices in the United States to access specific signals transmitted from the Global Navigation Satellite System known as Galileo. As a result of this action, consumers and industry in the United States will be permitted to access satellite signals from the Galileo system to augment the U.S. Global Positioning System (GPS) and benefit from improved availability, reliability, and resiliency of these position, navigation, and timing services in the United States.
- On November 15, 2018, the FCC initiated a comprehensive review of its orbital debris mitigation rules, including proposing new rules and updates to its current rules regarding orbital debris mitigation. These revisions would address technological and market changes that have occurred since

the adoption of the Commission's rules in 2004 and would incorporate improvements in debris mitigation practices into the Commission's rules, which will help preserve the space environment for continued innovation. The proposed changes include improvements to the disclosure of debris mitigation plans, as well as proposals related to satellite disposal reliability and methodology, deployment altitudes, and on-orbit lifetime, with a particular focus on large, nongeostationary satellite orbit systems. Other aspects of the proposals include rules for geostationary orbit license term extensions, as well as consideration of disclosure requirements related to several emerging technologies and new types of commercial operations.

- On November 15, 2018, the FCC proposed to streamline its rules by permitting some types of satellite networks to be licensed under a single license that would include both earth stations and space stations and by adopting rules that consider the network as a whole with respect to deadlines for beginning operations. The FCC also proposed to eliminate some annual reporting requirements for satellite operations.
- On November 15, 2018, the FCC proposed new rules applicable to earth stations in motion (ESIMs), such as earth stations located aboard ships, aircraft, and vehicles. The proposed rules would expand on previous rules adopted for ESIMs and cover communications with nongeostationary-orbit satellites operating in the fixed-satellite service.
- On August 1, 2019, the FCC adopted revisions to its rules that produced a streamlined application process for a category of satellites known as small satellites. The revisions created an alternative, lower-cost, more flexible authorization process for these smaller-scale operations. Under the new FCC process, applicants for small-satellite systems meeting certain characteristics, such as having a low number of satellites, a relatively short satellite on-orbit lifetime, and the ability to share radio frequency use with other operators, will be able to take advantage of streamlined processing.
- On September 26, 2019, the FCC adopted revisions to its rules applicable to the direct broadcast satellite (DBS) service. These rules align the FCC's DBS processing procedures with procedures used for geostationary-orbit fixed-service satellites. The revised rules adopt a process for considering

applications on a first-come, first-served basis, adopt deadlines and performance bond requirements for beginning operations to DBS services, and lengthen the standard license term for most DBS space stations. The FCC also ended a "freeze" on the filing of applications for DBS licensees.

During FY 2019, the FCC issued rulings facilitating the deployment and operations of a number of nongeostationary satellite systems designed to provide communications services, including high-speed broadband. These rulings included the following:

- On November 15, 2018, the FCC authorized Space Exploration Holdings, LLC (SpaceX), to construct, deploy, and operate a new satellite system consisting of up to 7,518 satellites operating in very-low-Earth orbit at approximate altitudes between 335 kilometers and 346 kilometers and utilizing the V-band. The FCC also authorized SpaceX to communicate using the V-band with the nongeostationary satellite system that the FCC had previously authorized during FY 2018, which would also utilize the Ku- and Ka-bands. Using the combined satellite systems, SpaceX would have the capacity to provide diverse geographic coverage and support a wide range of broadband and communication services for residential, commercial, institutional, governmental, and professional users in the United States and globally.
- On November 15, 2018, the FCC issued a ruling outlining the conditions under which Kepler Communications, Inc., could obtain a license for earth stations in the United States for use with its system, which would operate under the authority of Canada. The system would consist of up to 140 satellites operating at an approximate altitude of 500–600 kilometers and utilizing frequencies in the Ku-band. The planned satellite system would offer global connectivity for a range of communications uses, including transferring data from sensors and devices used in what is often referred to as the "Internet of Things."
- On November 15, 2018, the FCC issued a ruling outlining the conditions under which Telesat Canada can obtain a license for earth stations in the United States for communications in the V-band with its system, which will operate under the authority of Canada. The system would consist of

up to 117 satellites operating at approximate altitudes of 1,000 and 1,250 kilometers. This planned nongeostationary satellite constellation would provide high-speed, low-latency communications services.

- On November 15, 2018, the FCC issued a ruling outlining the conditions under which LeoSat MA, Inc, can obtain a license for earth stations in the United States for use with its system, which was planned to operate under the authority of the Netherlands, utilizing a French International Telecommunications Union filing. The system would consist of up to 78 satellites operating at an approximate altitude of 1,400 kilometers and utilizing frequencies in the Ka-band. The FCC subsequently declared the ruling to be null and void as of September 28, 2019, because LeoSat did not meet its obligation to maintain a performance bond until certain operational deadlines were met, as specified in the FCC's ruling.
- On April 26, 2019, the FCC granted a request from SpaceX for a modification of its authorization for a nongeostationary-orbit constellation utilizing Ku- and Ka-band spectrum, in order to reduce the total number of satellites in the constellation from 4,425 to 4,409 and to operate 1,584 of the authorized satellites at an altitude of 550 kilometers rather than 1,150 kilometers.
- On May 9, 2019, the FCC authorized Theia Holdings A, Inc., to construct, deploy, and operate a satellite system consisting of 112 satellites operating at an approximate altitude of 800 kilometers and utilizing the Ku-, Ka-, and V-bands. This planned nongeostationary satellite constellation would provide high-resolution Earth-imaging data in the United States and globally.

The FCC also granted authority for the operations of nongeostationary satellites, including small satellites, in low-Earth orbit for remote sensing activities. Specifically:

- On October 3, 2018, the FCC granted authority to BlackSky Global, LLC, to construct, deploy, and operate up to four satellites at orbital apogee altitudes ranging from 460 to 585 kilometers. On May 16, 2019, the FCC granted the request of BlackSky Global, LLC, for a license modification to change the range of orbital apogee altitudes to 435–585 kilometers, and

the specified propulsion system for one of its satellites to a water-based rather than butane-based propulsion system.

- On November 29, 2018, the FCC granted authority to Spire Global, Inc., to construct, deploy, and operate up to 872 satellites at orbital altitudes between 385 and 650 kilometers.
- On June 13, 2019, the FCC granted authority to DG Consents Sub, Inc., as part of a license modification for its existing constellation, to construct, deploy, and operate 12 remote sensing satellites. The satellites will operate at various orbital altitudes between 450 and 870 kilometers.

In FY 2019, the FCC authorized a number of other commercial communication satellite deployments and operations. These authorizations included the following:

- October 3, 2018: To Sirius XM Radio, Inc., to construct, deploy, and operate a satellite providing Satellite Digital Audio Radio Service at the longitude 85.15° west orbit location.
- October 3, 2018: To Sirius XM Radio, Inc., to construct, deploy, and operate a satellite providing Satellite Digital Audio Radio Service at the longitude 115.25° west orbit location.
- November 14, 2018: To Intelsat License, LLC, to construct, deploy, and operate a C-, Ku-, and Ka-band satellite to be located at the longitude 125° west orbit location. Intelsat was also authorized to operate the satellite in the L-band to provide support to the Federal Aviation Administration's Wide Area Augmentation System for air navigation.
- March 27, 2019: To DIRECTV Enterprises, LLC, to construct, deploy, and operate a Ka-band satellite to be located at the longitude 102.7° west orbit location.
- December 4, 2018: To Intelsat License, LLC, to construct, deploy, and operate a Ku-band satellite to be located at the longitude 85° east orbit location.

In addition, on June 20, 2019, the FCC granted the request of Space Logistics, LLC, in connection with an application granted in part during FY 2018, to permit telemetry, tracking, and command communications with its satellite-servicing vehicle, Mission Extension Vehicle–1 (MEV-1), following rendezvous, proximity operations, and docking of the MEV-1 with the Intelsat 901 spacecraft at a location

several hundred kilometers above the geostationary arc, and during the subsequent maneuver to and operation of the "stacked" spacecraft at the longitude 27.5° west orbit location. On the same date, the FCC also granted the request of Intelsat License, LLC, to modify its license to include authority related to these operations. Both licenses also included authority for future operations to raise the stacked spacecraft above the geostationary arc and to undock.

In addition to these commercial operations, the FCC continued to grant applications for experimental operations by nongovernmental small satellites. Many of the experimental grants by the FCC for small-satellite operations were to universities and institutions conducting research and developing new spacecraft technologies. The satellites' missions included testing new equipment for use on satellites, including communications and navigation technologies, propulsion systems, and solar sails, as well as measuring weather and climate conditions on Earth, measuring properties of the ionosphere, and tracking satellite orbital decay, among other things. Other experimental licenses granted in FY 2019 included grants for communications with launch vehicles and for testing satellites on a noncommercial basis for future commercial missions.

The FCC granted a number of license modifications and Special Temporary Authorizations for satellite networks. Many involved routine testing or redeployment of satellites with a multi-satellite system. Several of these actions, however, warrant particular mention:

- October 12, 2018: The FCC granted special temporary authority to Spaceflight, Inc., to communicate for a period of less than four hours with two nongeostationary spacecraft deployers, known as the Upper Free Flyer and Lower Free Flyer, in order to deploy up to 74 small spacecraft.
- May 22, 2019; July 10, 2019; July 25, 2019; and August 20, 2019: The FCC issued a series of grants of special temporary authority to DG Consents Sub, Inc., related to relocation of the WorldView-4 non geostationary-orbit satellite due to technical issues with the satellite's control movement gyros.
- June 13, 2019: The FCC granted the request of Hughes Network Systems, LLC, for a license modification to permit operation of the EchoStar XXIV satellite, also known as HNS-95W or Jupiter 3, at the longitude 95.2° west

orbit location using additional frequencies in the Ka- and V-bands for service in the United States.

- September 4, 2019: The FCC granted Iridium Constellation, LLC, special temporary authority for communications operations related to replacement of its last remaining first-generation satellite with a satellite in its second-generation Iridium NEXT constellation.
- September 6, 2019: The FCC granted EchoStar Satellite Operating Corporation special temporary authority to extend the service coverage area of the EchoStar 9 satellite at the longitude 121° west orbit location to cover the Bahamas for emergency operations following Hurricane Dorian.

The FCC also added non-U.S.-licensed space stations to its permitted list to allow the space station to provide domestic and international satellite service to U.S. earth stations that have routine technical parameters. These included the following:

- On February 26, 2019, the FCC added SES Americom, Inc.'s NSS-11 satellite to the permitted list, operating under the authority of the United Kingdom (Gibraltar) and using the Ku-band at the longitude 176° east orbit location.
- On September 12, 2019, the FCC added New Skies Satellites B.V.'s NSS-6 satellite to the permitted list, operating under the authority of the Netherlands and using the Ku-band at the longitude 169.5° west orbit location.

U.S. Department of Agriculture

USDA

The U.S. Department of Agriculture (USDA) provides leadership on food, agriculture, natural resources, rural development, nutrition, and related issues based on public policy, best available science, and effective management. Remotely sensed data and derived information directly support mission-critical work of the USDA. A wide variety of data and technology, including aerial and satellite imagery, high-quality elevation data, and ground-based collections validated with GPS, are used in daily operations.

Agriculture Research Service

As the primary research agency of the USDA, the Agricultural Research Service (ARS) conducts research to solve problems affecting global food security, agricultural air quality, biofuels, ecosystem services such as watersheds, and ways to adapt to climate change. ARS collaborates with NASA in partnership with other USDA agencies (the Natural Resources Conservation Service [NRCS], Risk Management Agency [RMA], World Agricultural Outlook Board [WAOB], Foreign Agricultural Service [FAS], National Agricultural Statistics Service [NASS], and Animal and Plant Health Inspection Service [APHIS]) to develop technologies that help the agencies carry out their missions. Partnerships with other Federal agencies, universities, industry, and state governments are integral to ARS research. ARS developed technologies for the management of water and soil resources, crop production, and rangeland resources. The sensor systems used by ARS included satellite

systems, airborne systems including small Unmanned Aerial Systems (sUAS), on-the-go sensors mounted on field equipment, and other ground-based systems.

Water quality and quantity management continued to be the largest area of emphasis for ARS remote sensing activities. Soil moisture remote sensing research continued with the development of algorithms for soil moisture estimation from aircraft and satellites. ARS scientists also contributed to the development of the next generation of satellite remote sensing systems through the Soil Moisture Active Passive (SMAP) mission, with ARS providing key evaluation validation data for the evolution of the algorithms to the most accurate and high-resolution soil moisture products available today. Researchers contributed extensively to the development and implementation of the ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) mission, which provides high-resolution evaporation stress estimates from the International Space Station. Additional research into more efficient fertilizer application using remote sensing of crop nitrogen status reduced excess fertilizer losses to the environment, thus leading to improved water quality and better economic returns to farmers.

Farm Service Agency

The Farm Service Agency (FSA) administers farm commodity, credit, conservation, disaster, and loan programs as laid out by Congress through a network of Federal, state, and county offices. Land-based information has always played a fundamental role in daily operations and administration of those programs. FSA used a diverse set of remotely sensed data, typically from traditional aerial images, to support a wide variety of agency activities. Examples of those applications are recording producer-reported crop plantings and supporting conservation, commodity, and agriculture-based lending programs.

FSA did not directly operate any crewed aircraft or Unmanned Aerial Systems (UAS) this past reporting period; however, it did issue several remote sensing contracts to acquire airborne imagery that required the use of the National Airspace System (NAS). The main contracts supported orthorectified imagery collection for the National Agriculture Imagery Program (NAIP). NAIP is a multi-department-funded program that provides current high-resolution imagery of the contiguous

United States (CONUS) into the public domain. The NAIP imagery is collected every two to three years, and is used by nearly all civilian Federal agencies as a base layer in their geographic information system (GIS) to support a wide variety of activities, such as conservation and land management. Complete border-to-border CONUS coverage under NAIP requires broad access to restricted and other special-use airspace. Data from several military areas are not typically collected due to national security concerns. Areas whose imagery was not collected in 2019 were Eglin Air Force Base, Florida, and Nevada Test and Training Range, Nevada.

FSA also uses remotely sensed data collected from space-based systems, such as the Moderate Resolution Imaging Spectroradiometer (MODIS), the Pleiades-HR constellation, and other high-resolution satellite imagery, to support disaster recovery programs, including Emergency Loan and Emergency Conservation Programs, on an ad hoc basis. In addition to the civilian-managed space-based systems, FSA received imagery from the National Geospatial-Intelligence Agency (NGA) through Maxar's Global Enhanced GEOINT Delivery (G-EGD) (formerly known as DigitalGlobe's Enhanced View Web Hosting Service) during 2019. FSA does not directly manage any space-based systems and acquires all remote sensing data from other Federal agencies and commercial vendors.

Foreign Agriculture Service

The Foreign Agricultural Service's (FAS) Global Market Analysis (FAS/GMA) program area serves as a major source of objective and reliable global agricultural production information to the USDA's monthly World Agricultural Supply and Demand Estimates (WASDE) report, the primary source of the USDA's global commodity outlook. The monthly WASDE report provides public access to information affecting world food security and is crucial to decisions affecting U.S. agriculture, trade policy, and food aid. The Office of Global Analysis (FAS/OGA) uses satellite imagery at regional, national, and subnational scales to operationally monitor and analyze monthly changes in global crop production. FAS archives and displays monthly, country-level crop production, supply, and distribution (PSD) data from the USDA's WASDE report on the FAS PSD Online website at *https://apps.fas.usda.gov/psdonline/app/index.html#/app/home*.

During 2019, the International Production Assessment Division (IPAD) operated the remote sensing program at FAS/GMA. IPAD is an operational user of remotely sensed imagery and processed multiple U.S. and international sources of global imagery and satellite-derived weather information. Landsat 7 and 8, as well as Sentinel 2A and 2B, served as the primary satellites used by FAS/GMA/IPAD for mapping crop area and crop type for numerous countries worldwide. NASA's MODIS sensor, on board the Aqua and Terra satellites, was used by IPAD to monitor crop conditions and relative crop yields. The USDA–NASA Global Agricultural Monitoring (GLAM) web system displayed and archived historical MODIS-Terra (i.e., 2000–present) and MODIS-Aqua (i.e., 2002–present) Normalized Difference Vegetation Index (NDVI) imagery, and the GLAM-NDVI-MODIS web interface (*http://glam1.gsfc.nasa.gov/*) easily allowed public users to analyze and compare current crop conditions with past years' crop conditions. FAS/GMA plans to utilize NDVI time-series data from the Visible Infrared Imaging Radiometer Suite (VIIRS) sensor as a replacement for the NDVI-MODIS (Terra and Aqua) data streams that will end after 2020.

FAS/GMA also maintained several public global agricultural datasets by processing, archiving, and displaying a variety of satellite imagery products on the FAS/GMA Crop Explorer web system. Crop Explorer allows users to monitor, analyze, and display rainfall, temperature, soil moisture, and vegetation conditions by utilizing satellite imagery from NASA's Global Precipitation Measurement (GPM), NOAA's Polar-orbiting Operational Environmental Satellites (POES), and the European Space Agency's Proba-V, as well as satellite-derived weather information from the U.S. Air Force's 557th Weather Wing. In addition, the Global Reservoir and Lake Monitor (G-REALM) allows users to monitor and display reservoir and lake water heights by utilizing satellite radar altimeter data from NASA's Ocean Topography Experiment (TOPEX)/Poseidon, Jason-1, Jason-2, and Jason-3 satellites (*https://ipad.fas.usda.gov/cropexplorer/*). Lastly, the Global Agricultural and Disaster Assessment System (GADAS) is a new state-of-the-art geographic information system available to the public online. This system integrates a vast array of highly detailed Earth observation data streams from NASA, NOAA, the U.S. Air Force, and other agencies, with tools and cropland datasets to support agricultural and disaster assessment analysis. GADAS will help USDA/FAS remain a leader in the

use of geospatial data for crop condition monitoring and support collaboration between FAS teams working around the globe. (Find GADAS at *https://ipad.fas.usda.gov/* or directly at *https://geo.fas.usda.gov/GADAS/index.html*.)

FAS/GMA was part of the early-adopter program for Soil Moisture Active Passive (SMAP), and the USDA's global crop production monitoring system was enhanced by the SMAP two-layer soil moisture products processed by the USDA's Agricultural Research Service (ARS) and NASA researchers. The SMAP two-layer soil moisture product currently operates at 25-kilometer resolution.

FAS/GMA managed the USDA's Satellite Imagery Archive (SIA) program and displayed all moderate-resolution satellite imagery archived via SIA's Archive Explorer (AE). In 2000, the USDA's Remote Sensing Coordinating Committee (RSCC) established the SIA program, which is chaired by the USDA's Remote Sensing Advisor. During 2019, USDA/FAS purchased satellite imagery with 22-meter spatial resolution from the Deimos-1 and UK-DMC2 (Disaster Monitoring Constellation) and archived it at SIA's AE. FAS/OGA/SIA also provided funding to collect Advanced Wide Field Sensor (AWiFS) (56-kilometer) and Linear Imaging Self Scanning (LISS)–III Sensor (24-kilometer) imagery from the Indian Resourcesat–2 (IRS-2) satellite. The IRS-2 imagery is now available for download through the USGS Earth Explorer website at *https://earthexplorer.usgs.gov/*. The USDA's National Agricultural Statistics Service used Deimos-1, UK-DMC2, and IRS-2 satellite imagery covering the lower 48 states to map crop type for the 2019 United States crop season.

Forest Service

As the primary forestry agency of the United States and the largest agency in the USDA, the U.S. Forest Service (USFS) continues to sustain the health, diversity, and productivity of the Nation's forests and grasslands to meet the needs of present and future generations. This work encompasses partnerships with states, Tribes, and other Federal agencies to address forestry and natural resource issues; administration and management of 154 national forests and 20 national grasslands collectively known as National Forest System (NFS) lands, totaling 193 million acres; and assistance to private land owners and state, Tribal, and community

forestry agencies in the stewardship of approximately 500 million acres of non-Federal forest lands.

In FY 2019, the USFS collaborated with NASA, NOAA, the USGS, other agencies, and other external agency partners and cooperators to apply operational satellite and airborne imagery and the most advanced remote sensing and geospatial technologies. Specific accomplishments included the following:

- Planned, organized, and conducted a joint Forest Service/NASA workshop entitled "Forest Service/NASA Applications Workshop: Satellite Data to Support Natural Resource Management in April 2019." The three-day workshop focused on sharing and demonstrating the capabilities of NASA data products, as well as establishing connections and strengthening partnerships between NASA and the USDA Forest Service.
- Collected comprehensive Earth Observing System (EOS), MODIS, and Suomi NPP VIIRS near-real-time data and Landsat 8 Operational Land Imager (OLI) data via the USGS's Earth Resources Observation Systems (EROS) for the United States and Canada. Provided operational processing and disseminated near-real-time fire-mapping and geospatial data products to fire managers and the general public, including all science-sanctioned fire detection algorithms for MODIS (1-kilometer), VIIRS (750-meter and 375-meter) and Landsat (30-meter). (See *https://fsapps.nwcg.gov/afm/.*)
- Continued activities with NASA Goddard Space Flight Center's Direct Readout Laboratory under a USFS-NASA interagency agreement to test and operationally implement near-real-time satellite data-processing technologies, including land, atmospheric, and ocean science–processing algorithms for EOS and Suomi NPP sensors, to support evolving resource management and operational information needs. (See *https://fsapps.nwcg.gov/directreadout/.*)
- Continued operational processing and analysis of MODIS and Landsat imagery for systematic detection of damage and changing health conditions in Federal, state, and private forested lands throughout the continental United States. Monitoring data products provided early warning information to Forest Health Protection staff of forest areas potentially

affected by pests/pathogens and supported targeted monitoring and suppression activities. Also continued to initiate efforts to leverage operational VIIRS imagery for comprehensive forest monitoring and ensure future continuity with current MODIS-based monitoring approaches.

- Utilized MODIS imagery to conduct coarse-level forest damage assessments for large geographic areas of the continental United States in the immediate aftermath of significant forest disturbance events. This strategic information supported the agency in targeting areas for fuels management activities and/or areas where higher-resolution forest damage assessments are required.
- Continued to maintain and distribute 250-meter forest attribute data surfaces derived from MODIS imagery and other geospatial predictor data using nearest neighbor imputation methods. (See *http://data.fs.usda.gov/geodata/rastergateway/forest_type/index.php*.)
- Continued to maintain and distribute 250-meter forest carbon estimates derived from MODIS imagery and other geospatial predictor data using nearest neighbor imputation methods. (See *http://data.fs.usda.gov/geodata/rastergateway/biomass/index.php*.)
- Continued coordination with NASA Ames Research Center to upgrade Autonomous Modular Sensor (AMS) electronics and sensor components and further develop the AMS firmware and software for onboard processing system capabilities and user interface to support operational integration flights on USFS aircraft.
- Operationally applied Landsat 7 Enhanced Thematic Mapper (ETM) and Landsat 8 OLI imagery to respond to 78 requests to map the location, extent, and severity of large wildfires amounting to more than 650,000 acres in FY 2019. These rapid-response products supported postfire emergency stabilization/hazard-mitigation activities conducted by Forest Service Burned Area Emergency Response (BAER) teams. (See *https://fsapps.nwcg.gov/baer/*.)
- Applied Landsat 7 ETM and Landsat 8 OLI imagery to respond to map and estimate postfire basal area loss and canopy cover loss for 119 large wildfires totaling nearly 3.1 million acres in FY 2019. These products

supported forest restoration planning management activities and the efficient use of resources to support those activities. (See *https://fsapps.nwcg.gov/ravg/*.)

- Continued to apply Landsat 4/5 Thematic Mapper (TM), Landsat 7 ETM, and Landsat 8 OLI imagery to inventory, map, and characterize historical large fires to assess the effectiveness of national fire management policies as part of the Monitoring Trends in Burn Severity (MTBS) project. MTBS mapping activities through FY 2019 included the completion of an additional 1,296 fires, which increased the extent of the historical MTBS data record to include 22,969 fires covering more than 165 million acres of burned lands. (See *https://www.mtbs.gov*.)
- Coordinated with the University of Maryland, NASA, and the USGS under the auspices of a NASA Research Opportunities in Space and Earth Sciences (ROSES) A35 Wildfires Project to execute Landsat 8's active fire detection algorithm, refine as needed, and provide output products to support USFS operational fire support activities. FY 2019 efforts also included advancements on extending the Landsat 8 algorithm to support the development of an active fire detection algorithm for Sentinel 2A/2B.
- Continued technology transfer activities between the USFS and Ames Research Center on wildland fire remote sensing–related technologies under the guidance of the Tactical Fire Remote Sensing Advisory Committee (TFRSAC), which is a technical exchange forum jointly cochaired by NASA and the USFS.
- Used imagery from Landsat 8 OLI and NAIP to initiate, complete, and update mid-level vegetation-mapping, riparian-mapping, and Field Sampled Vegetation (FSVeg Spatial) update products for national forest lands and adjacent land areas throughout the country. Mapped areas included six National Forests encompassing approximately 10 million acres.
- Successfully built Tree Canopy Cover (TCC) data for 2016 for CONUS, coastal Alaska, Hawaii, Puerto Rico, and the U.S. Virgin Islands, using imagery from Landsat and NAIP.
- Used Landsat TM/ETM/OLI and NAIP imagery in conjunction with other core geospatial datasets to conduct ecological land-type associations

and soil-type mapping on NFS lands in the northeast and western United States, which the USFS, Natural Resources Conservation Service (NRCS), and other agencies apply to resource management, planning, and decision making. (See *http://www.fs.fed.us/eng/rsac/programs/teui/about.html*.)

- Progressed toward a comprehensive and consistent land-cover/land-use monitoring system, the Landscape Change Monitoring System (LCMS), for the continental United States. LCMS utilizes Landsat TM/ETM/OLI time-series stacks within Google Earth Engine to detect and monitor land-cover/land-use change from the mid-1980s to the present across all administrative ownerships. Efforts included the continued development of an annual CONUS change product since 1984. In FY 2019, the 1984-to-2017 CONUS change product was extended to include 2018. This effort is being conducted in collaboration with several Federal and academic partners. (See *http://landsat.gsfc.nasa.gov/?p=10868*.)
- Continued to develop and refine standards and practices for integrating light detection and ranging (lidar) into forest and resource management (defining acquisition specifications, performing data-quality assessments, developing analysis/modeling procedures for forest parameters, etc.).
- Continued to expand USFS involvement in the USGS 3D Elevation Program to ensure consistent acquisition specifications and minimize redundant collections by partnering with other state and Federal entities on data acquisitions.
- Continued to provide operational web mapping and data services for NAIP imagery and selected moderate resolution imagery from NASA satellite assets for consumption/use by Forest Service and Bureau of Land Management staff. The nearly one-petabyte data archive that provides the source data for these services provides spatially and temporally comprehensive coverage for the United States and is essential for daily Forest Service operational business information needs.
- Forest Inventory and Analysis (FIA) and Forest Health Protection (FHP) staff continued in FY 2019 to utilize CONUS and OCONUS (Outside CONUS) Landsat 8, MODIS, and NAIP imagery products to support

inventory and monitoring of the Nation's forests, including mapping and use in post stratification to improve forest attribute estimates.

- Conducted a geotechnical evaluation on joint lidar-hyperspectral datasets and analyses for use in forest applications. The pilot study assessed the practicality of the use of NASA's Goddard's Lidar, Hyperspectral, and Thermal Imager (G-LiHT) data for land-cover classification. Results of the study indicated that the integration of G-LiHT lidar and hyperspectral data improved land-cover classification accuracy.
- FIA and FHP continued in FY 2019 to use NASA G-LiHT data with NAIP imagery throughout CONUS to assess and monitor forest conditions. Additionally, FIA worked with NASA scientists to continue the use G-LiHT data to support forest inventory of interior Alaska, including initiating investigations for its use to estimate tree canopy height and canopy cover.

National Agricultural Statistics Service

The National Agricultural Statistics Service (NASS) used remote sensing data to construct and sample area frames for agricultural statistical surveys; estimate crop area and yield; visualize crop condition and crop area via data-visualization applications; impute for survey non-response; and provide geospatial data products for decision support to assess flooding impact on agriculture from Hurricane Dorian, Tropical Storm Barry, and extreme springtime precipitation in the Midwest. NASS used Landsat imagery, digital NAIP imagery, and other remotely sensed inputs for the contiguous United States to select the yearly area-based samples for the 2019 June Area Survey. In addition, NASS finished updating a new area-based sampling frame for Texas.

The remote sensing acreage estimation program used satellite imagery from the Disaster Monitoring Constellation (DMC), Landsat 8, Sentinel-2, and Resourcesat-2 to produce crop acreage estimates for crops at state, agricultural statistics district (ASD), and county levels. Remote sensing–based acreage indications for all states were derived from the Cropland Data Layer (CDL) for all market-sensitive crops. The DMC imagery was provided by the Foreign Agricultural Service Satellite

Imagery Archive, which provided growing-season coverage with DMC imagery through a cooperative partnership. The NASS Agricultural Statistics Board (ASB) utilized the remote sensing acreage indications as independent input for setting official estimates for monthly crop production reports. In addition, NASS distributed the CDL for 48 states to stakeholders for the previous 2018 crop season via the USDA Geospatial Data Gateway and the CropScape application at *https://nassgeodata.gmu.edu/CropScape*.

The NASS online geospatial GIS application CropScape continued to provide data users with access to a variety of geospatial resources and information, including all historical CDL data and derivative cultivated data-layer and crop-frequency data-layer products. This application offers advanced tools such as interactive visualization, web-based data dissemination, geospatial queries, and automated data delivery to systems such as Google Earth. It delivers crop-specific land-cover data and visualization tools directly to the agricultural community without needing specialized expertise or GIS software. This information can be used for addressing issues related to agricultural sustainability; land-cover monitoring; biodiversity; and extreme events such as flooding, drought, and disaster assessment.

The CDL data and the CropScape Web application were used directly for June Area Survey imputation. The CDL data, which have an 11-year record of planting information for every field for the contiguous 48 states, is a reliable alternative and independent data source for imputation. Moreover, CropScape can be used for accessing, navigating, visualizing, and summarizing the CDL data within selected areas of interest. This tool and CDL data are used to help NASS statisticians estimate acreage information missing from non-respondent and inaccessible farmers.

Geospatial decision-support data products were delivered for rapid flooding assessments, including from Hurricane Dorian, Tropical Storm Barry, and the extensive flooding in the Midwest in May and June of 2019. Dorian, Barry, and the Midwest assessments included flooding extent and potential crop and livestock losses. The products included crop and pastureland inundated areas, estimated precipitation totals, CDL crop area maps, and wind swaths or surface winds overlaid onto crop areas identified from the CDL product over impacted areas and available on *https://www.nass.usda.gov/Research_and_Science/Disaster-Analysis/*. The Sentinel-1 Synthetic Aperture Radar (SAR) satellite was used to provide a

see-through-the-clouds opportunity to capture real-time storm inundation over crop and pasturelands, providing flooding assessments and sharing of critical data for both USDA and Federal Emergency Management Agency (FEMA) usage.

NASS utilized NASA MODIS NDVI and Land Surface Temperature (LST) products for modeling corn and soybean yield estimates covering the 16 largest corn and 11 largest soybean production states. Updated yield estimates were delivered operationally to the ASB as an independent indication for setting official August, September, and October yield estimates by state, ASD, and county.

The web-based national vegetation condition geospatial portal VegScape (*https://nassgeodata.gmu.edu/VegScape*) continued to deliver timely crop condition vegetation indices based on MODIS daily, weekly, and biweekly products throughout the growing season. VegScape showed crop condition/vegetation greenness and drought anomaly assessments. NASS continued monitoring the ongoing California drought, providing monthly growing-season CDL-based fallowed-land estimates for California water resource stakeholders.

NASS is continuing to collaborate with George Mason University, the USDA/Risk Management Agency, and the University of Colorado in developing a remote sensing–based flood disaster crop loss assessment system. The proposed system will provide the capability of flood disaster crop acreage loss and crop yield loss assessments using NASA remote sensing data and science results.

Natural Resources Conservation Service

NRCS helps America's farmers, ranchers, and forest landowners conserve the Nation's soil, water, air, and other natural resources. To fulfill this mission, NRCS assesses, acquires, develops, interprets, analyzes, and delivers natural-resource information to enable knowledge-based natural-resource planning and decision making at all landscape levels. Various types of geospatial systems, data, and information are crucial to the successful delivery of NRCS services.

Orthoimagery, elevation data, and Global Positioning Systems are essential geospatial data integrated into NRCS program applications, service centers, state offices, and national centers. Since the 1930s, NRCS (formerly the Soil Conservation Service) used aerial photography and orthoimagery for conservation

and soil survey purposes. Today, NRCS offices use geospatial data daily to support conservation programs.

NRCS coordinates acquisitions of orthoimagery and digital elevation data with other Federal and state agencies through interagency committees like the National Digital Orthoimagery Program (NDOP) and the USGS 3D Elevation Program (3DEP). Participation in NDOP and 3DEP assists NRCS in maximizing geospatial investments and avoiding duplication of acquisitions for orthoimagery and digital elevation datasets.

Aerial Imagery

In FY 2019, NRCS executed a contract to acquire high-resolution aerial photography (4-inch ground-resolving distance) and scans of more than 70,000 sites in the contiguous United States, 477 sites in Puerto Rico and the U.S. Virgin Islands, and 344 sites in Hawaii. All the sites possess confidential location information. NRCS continued to use natural-color negative film for these collections. Despite the known advantages of direct digital imagery, film continued to be the least costly method to acquire high-spatial-resolution imagery for the National Resources Inventory (NRI). The scanned film imagery is georeferenced and interpreted at one of NRCS's three Remote Sensing Labs. The resulting data were sent to the Center for Survey Statistics and Methodology at Iowa State University for statistical analysis. (See *https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/*.)

Through the Agricultural Conservation Easement Program (ACEP), the Healthy Forest Reserve Program (HFRP), and the Emergency Watershed Protection Program–Floodplain Easements (EWPP-FPE), NRCS holds title or enforcement rights to approximately 17,800 Stewardship Land easements, providing protection to more than 3.4 million acres nationally. Stewardship land easements are easements that the agency (as NRCS, the Soil Conservation Service [SCS], or the Commodity Credit Corporation [CCC]) acquired on behalf of the United States as a holder or for which it has other responsibilities outlined in the easement deed. Annual monitoring of these easements is critical to ensure that the objectives of each easement program and relevant easement authorities, as well as legal requirements, are being met on the enrolled lands. Additionally, NRCS

is required to report the "condition" of its easements as part of its annual federal financial accountability reporting. Starting in FY 2014, the NRCS conducted a pilot project using high-resolution direct digital imagery to test the efficiency of having imagery available to state offices early in the fiscal year for monitoring activities. In FY 2019, NRCS continued the pilot project to acquire imagery for monitoring purposes. Information on easement programs can be found at *https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/programs/easements/.*

The National Agriculture Imagery Program (NAIP) is a high-resolution imagery program that usually collects data during leaf-on time periods during the summer months. This dataset is the foundation layer for geospatial data used in USDA offices and those of our cooperators. NRCS; USFS; USGS-DOI; and the NAIP Leader, FSA, have successfully funded and supported NAIP since the program's inception in 2003. NAIP orthoimagery is used extensively within NRCS and is used in most NRCS offices in the continental United States. NAIP orthoimagery is delivered to NRCS at a 1.0-meter or higher ground resolution and with four multispectral bands (Natural Color and Color Infrared [CIR]). NRCS makes use of NAIP in many programs, such as the Web Soil Survey (*https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm*) and Conservation Planning (*https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/cgate/*), and it is used as the base imagery for NRI for orthorectification. NRCS makes NAIP data available to the general public via compressed county imagery mosaics on the USDA Geospatial Data Gateway at *https://gdg.sc.egov.usda.gov/.* In FY 2019, NAIP collected 23 states' worth of imagery. All were collected at 0.6-meter resolution and in four multispectral bands (Natural Color and CIR). NAIP collects data from all areas of the United States, including agricultural land, public lands (Federal, state, and local), and urban areas.

Satellite Imagery

In 2019, NRCS responded to geospatial imagery needs from all states and territories, including Puerto Rico, the U.S. Virgin Islands, Guam, the Commonwealth of the Northern Mariana Islands, American Samoa, and parts of Micronesia. NRCS requires high-resolution imagery at one meter or higher for most agency programs. Acquisition of imagery in non-CONUS areas was challenging because

of remoteness and weather. NRCS used satellite imagery from the DigitalGlobe EnhancedView Web Hosting Service (*https://evwhs.digitalglobe.com*) and purchased imagery from commercial sources for areas such as these and over-restricted airspace. NRCS also used DigitalGlobe imagery for pre- and post-event disaster response and in cases where other imagery is outdated.

Elevation

NRCS participates in the USGS 3DEP to acquire high-quality 3D elevation data through remote sensing. (See *https://nationalmap.gov/3DEP/*.) The map depicts areas of actual lidar topographic acquisition projects that NRCS and 3DEP partners awarded in FY 2019.

In FY 2019, 3DEP and its partners significantly increased the coverage of lidar and IfSAR, resulting in a cumulative total of 64 percent of the Nation with 3DEP-quality data available or in progress. NRCS invested $21.3 million of the $136.8 million total 3DEP investments for FY 2019 awards. The goal of 3DEP is to complete the acquisition of nationwide lidar (IfSAR in Alaska) in eight years to provide the first-ever national baseline of consistent high-resolution elevation data—both bare-earth and 3D point clouds—collected in a timeframe of less than a decade.

Use of Positioning, Navigation, and Timing Signals from Space

The United States Global Positioning System (GPS) is the primary source of space-based signals for Positioning, Navigation, and Timing (PNT). The NRCS utilizes GPS signals from space, as well as the FAA Wide Area Augmentation Service (WAAS) signals and ground-based cellular Real Time Kinematic (RTK) corrections to space-based PNT to put conservation practices on the ground daily in every state of the United States, as well as in the Caribbean and Pacific basins. The use of PNT services, free from radio spectrum interference, continues to support the NRCS mission of "Helping People Help the Land." Please see *https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/newsroom/features/?cid=nrcseprd1441031* for more information regarding NRCS conservation activities enabled and enhanced by GPS PNT services.

Employees of NRCS, located in more than 2,000 Field Service Centers across the United States, as well as in the Caribbean and Pacific basins, performed the following activities utilizing GPS and WAAS PNT services in FY 2019:

- NRCS technical specialists and contractors used GPS as an aid for the collection of National Resources Inventory (NRI) plant composition and ecology information in 49 states on more than 3,000 sample areas known as area segments. Most area segments contain three individual sample points. Each sample point represents a physical location on Earth's surface. NRCS and contracted personnel used GPS PNT services to navigate to two of the three sample points and perform location validation upon arrival at the points. Accurate navigation, free from radio spectrum interference, to sample sites was required to achieve statistically valid data collection. Results of the data collection were compiled and analyzed for use in reports such as the "2019 NRI Rangeland Resource Assessment" report and the "2019 NRI Pastureland Assessment Report." Please see *https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/* for further information on the data produced by this nationwide field data collection effort.
- The National Resources Inventory contracted the collection of aerial imagery on nearly 72,000 area segments in FY 2019. Accurate GPS PNT airborne navigation, free from radio spectrum interference, to sample site locations continues to be required for data collection to support trend analysis. Results of the aerial imagery component of NRI continue to be published in reports that support the 1972 Rural Development Act. Please see *https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/* for further information.
- Many NRCS states utilized GPS PNT services to navigate to and document the condition of conservation easements under the authority of the Agricultural Conservation Easement Program (ACEP). More NRCS personnel in multiple states utilized GPS PNT services along with smart devices to collect monitoring information on thousands of easements across the country. The collected data, as well as supporting photos and notes, were uploaded into an enterprise content management system and

were used to support the analysis of easements. GPS PNT services aided aerial imagery contractors in acquiring thousands of aerial images for contract compliance review. Private-sector Registered Land Surveyors used survey-grade GPS PNT services to establish and record boundaries of new agricultural easements and validate the boundaries of existing easements.

- NRCS soil scientists routinely used GPS PNT services to navigate to soil-sampling sites and conduct follow-up investigations. GPS PNT services were also used to provide technical soil survey assistance to farm and ranch operators.
- The NRCS Water and Climate Center continued to utilize GPS PNT services to map locations of instrumentation, provide timing for telemetry signals, and enhance safety for employees. The coordination and delivery of data from 867 Snow Survey Telemetry (SNOTEL) stations and 226 Soil Climate (SCAN) stations required nanosecond precision that interference-free timing signals from GPS PNT services provide. The Water Climate Center also utilized the NOAA Geostationary Operational Environmental Satellite (GOES) network to provide telemetry services for remote monitoring sites at more than 25 locations. Telemetry data services have also been procured for Iridium satellite commercial communications on nearly 100 locations.
- In FY 2019, the NRCS and cooperating partners utilized GPS, along with other geospatial data, to put conservation practices on the ground. GPS positions marked the locations of resource concerns on the landscape. Agency personnel and cooperating partners transferred resource concern position information from GPS receivers to a USDA Enterprise Geographic Information System (GIS) application called Conservation Toolkit. Planners used the Toolkit to prepare conservation and alternative plan maps. Farm and ranch owner/operators used the plan maps to choose conservation practices that addressed the identified resource concerns. They also used GPS to verify measurements and document established practices for contract cost-sharing payments. NRCS clients, agricultural owners, and operators utilized GPS PNT services to mark up NRCS plan maps while in the field, identify new or additional resource concerns, and

map crop damage. Use of GPS PNT services increased among NRCS clients, with the top uses being assisted steering of machinery, precision application of nutrients and pesticides, and harvest yield monitoring. The use of interference-free GPS PNT services enables producers to implement precision farming practices that save fuel and reduce the amount of fertilizer and pesticides applied to the landscape. More agricultural producers are utilizing sUAS to perform monitoring of crop health and map damage. The use of GPS PNT services was essential for accurate mapping of crop issues by sUAS.

- NRCS engineers utilized GPS PNT services to perform detailed topographic surveys of agricultural operations to support conservation planning. Additional GPS surveying was performed to design and lay out conservation practices that managed or controlled the flow of water across the landscape. Many NRCS contractors utilized GPS through all phases of engineering design and construction. Examples of the use of design-to-construction machine control, enabled by the use of GPS PNT services, were reported in Alaska and Wyoming. In each case, machine control was used to achieve more accurate results and reduce time and cost to restore stream channels and waterways damaged by flooding. NRCS engineers have explored the use of sUAS to perform as-built inspection of drainage structures and rehabilitated dams. The use of interference-free GPS PNT services for engineering design and construction as well as sUAS inspection operations assures accurate results that can be compared to future inspections for the identification of changes during the monitoring of structure performance and integrity.
- Acquisitions of aerial imagery, such as NAIP and aerial elevation acquisitions using lidar, were enabled by the use of GPS PNT services. NAIP imagery and lidar were utilized by all NRCS conservation planning, engineering, and inventory/monitoring activities and were core to the implementation of the agency mission. The use of interference-free GPS PNT services in the acquisition of geospatial base imagery and elevation data provided a high level of quality assurance for agency end users and external customers.

- NRCS invested more than $2,955,000 in FY 2019 for the replacement of existing GPS PNT technology for engineering survey and for conservation planning applications. The provision of an interference-free radio spectrum environment for GPS PNT services will assure continued Return on Investment (ROI) in succeeding years.

Risk Management Agency

The USDA's Risk Management Agency (RMA), established in 1996, serves America's agricultural producers through effective, market-based risk management tools to strengthen the economic stability of agricultural producers and rural communities. RMA manages the Federal Crop Insurance Corporation (FCIC) to provide innovative crop insurance products to America's farmers and ranchers. Geospatial systems and analytics data, including space-based remote sensing systems, have played a fundamental role in RMA's program delivery, particularly in the compliance and oversight program areas.

Through crop insurance, RMA provided assistance to farmers and ranchers impacted by natural disasters, including flooding, hurricanes, and fires. In 2019, RMA used remote sensing data, such as Landsat, Sentinel-2, DMC, MODIS, and high-resolution aerial and satellite imagery for supporting crop insurance and program integrity. Many of these imagery products were collected as a result of the USDA's interagency coordination.

RMA incorporated many different geospatial decision-support products that have been provided to the USDA and RMA leadership for situational awareness. These products help mitigate many natural disasters that have significant impacts to agricultural areas that use crop insurance. The products included impacted program estimates, estimated precipitation, and natural-disaster extents with such things as flooding, hurricanes, and wildfires. Orthoimagery, elevation data, and GPS information were essential geospatial data integrated into RMA program applications. RMA offices used geospatial data daily to support crop insurance.

RMA staff were active participants in Science Teams, such as the USGS-NASA Landsat Science Team and the USDA Soil Moisture Working Group that focuses on the use of data from the NASA SMAP mission. As an operational user of

remote sensing products, RMA's participation in these work groups provided insight to scientists in developing applications that benefit crop insurance delivery and oversight, as well as farmers and ranchers across America.

In addition, RMA often partnered with scientists and researchers to develop products to meet agency business needs, including with Oregon State University–Parameter-elevation Regressions on Independent Slopes Model (PRISM); George Mason University and USDA NASS on developing an agricultural flood-loss estimation system; and Tarleton State University–Center for Agribusiness Excellence (CAE) on integrating satellite imagery for enhancing program integrity models.

National Science Foundation

NSF

The National Science Foundation (NSF) continued to serve as the lead Federal agency for the support of ground-based astronomy and space science. Through the divisions of Astronomical Sciences, Physics, Atmospheric and Geospace Sciences, and Polar Programs, the NSF sponsored a broad base of observational, theoretical, and laboratory research aimed at understanding the states of matter and physical processes in the universe. Areas of research ranged from the most distant reaches of the universe and the earliest moments of its existence to nearby stars and planets—including our own Sun and planetary system—as well as Earth's atmosphere and space environment.

Division of Astronomical Sciences

The Division of Astronomical Sciences (AST) within the Mathematical and Physical Sciences (MPS) Directorate supported the development of advanced technologies and instrumentation for astronomical sciences, in addition to providing core support for the optical and radio observatories with state-of-the-art instrumentation and observing capabilities accessible to the community on the basis of scientific merit. The NSF's national astronomical facilities included the National Radio Astronomy Observatory (NRAO), the Arecibo Observatory (AO), the National Optical Astronomy Observatory (NOAO), the Green Bank Observatory, and the National Solar Observatory (NSO). The NSF also served as the executive agency for the Gemini Observatory—an international partnership operating optical/

infrared telescopes in both the Northern and Southern Hemispheres—providing the United States' share of support for the program.

During FY 2019, AST, in partnership with the European Union, Canada, Japan, the Republic of Korea, and Taiwan, continued science operations of the Atacama Large Millimeter/Submillimeter Array (ALMA), an interferometric array located near San Pedro de Atacama, Chile. ALMA continued to receive a high number of observing proposals (approximately 1,800). Capabilities offered to the community included simultaneous observations with arrays of 12- and seven-meter-diameter antennas, observations with antenna separations of up to 16 kilometers, and observations at frequencies of up to 900 gigahertz. ALMA continued to provide unique insights across a broad range of topics, including planets and planet formation, proto-stellar and debris disks, low- and high-mass star formation, stellar evolution, normal galaxies, galactic centers, and galaxy formation and evolution. ALMA, as a component of the Event Horizon Telescope (EHT), was a major contributor to the observation of the supermassive black hole in M87.

Construction of the NSF's Daniel K. Inouye Solar Telescope (DKIST) continued through FY 2019. DKIST is the result of the collaboration of scientists from more than 20 institutions representing a broad segment of the U.S. solar physics community, and it had previously earned the strong recommendation of the National Research Council of the National Academy of Sciences. After completion, DKIST is planned to be the world's flagship ground-based telescope designed specifically for the study of solar magnetic fields on scales as small as 30 kilometers. The baseline cost for the DKIST project is $344.13 million. The project is approximately 93 percent complete and is both on budget and on schedule. In early FY 2019, DKIST achieved its first images of starlight and completed its first pointing model using a temporary Nighttime Acquisition Telescope mounted at the telescope prime focus. The project continued to carry out the critical Integration, Testing and Commissioning (IT&C) phase of construction. In preparation for the next Level-1 milestone, "first (Sun)light," installation of the Gregorian Optical Station was completed, along with installation of the Visible Broadband Imager (VBI) instrument and Wave Front Correction (WFC) system in the Coudé lab.

The National Solar Observatory (NSO) is the lead organization for the construction of DKIST. In FY 2019, funding for DKIST operations completed a

five-year ramp to a steady-state level of approximately $16.5 million per year. NSO is currently building a new DKIST Data Center at its headquarters in Boulder, Colorado. The Data Center is expected to process up to 12 terabytes of DKIST data per day. In FY 2019, the Data Center passed its Critical Design Review, receiving a recommendation to move forward with implementation from the review panel.

Personnel from MPS-AST, along with colleagues from the Directorate for Geosciences' Division of Atmospheric and Geospace Sciences (GEO-AGS), participated in the National Science and Technology Council's (NSTC) Space Weather Operations, Research, and Mitigation (SWORM) multi-agency task force. The NSTC tasked SWORM with developing a National Space Weather Strategy (NSWS) and an associated National Space Weather Action Plan (NSWAP). NSO's Global Oscillations Network Group (GONG) provides detailed synoptic solar data crucial to operational space weather forecasting. Operations of the GONG facility are jointly funded through a five-year Interagency Agreement between the NSF and the National Oceanic and Atmospheric Administration.

Construction of the Large Synoptic Survey Telescope (LSST) project continued in FY 2019, with realized risks remaining within the originally assigned cost and schedule contingencies. Construction is over 73 percent complete. The Telescope Mount Assembly, the primary-tertiary mirror, the secondary mirror, and the mirror coating plant have all safely arrived on the summit. The coating plant has successfully delivered a science-grade coating to the secondary mirror. The Base Facility in La Serena was also completed in FY 2019. In LSST's planned ten-year prime mission, imaging the entire accessible sky many hundreds of times, the multicolor survey will populate a science-ready database of unprecedented size, enabling breakthrough research in dark energy and dark matter, in galactic structure, and in solar system astronomy. The relentless, repeated observations will also open up the time domain and revolutionize the study of transient events. The Federal partners, NSF and the Department of Energy (DOE), expect this survey to generate about 20 terabytes of data every night, night after night, throughout its operational life. DOE is funding the camera in a project led by the SLAC National Accelerator Laboratory. NSF is funding the telescope, building, site, network and software pipelining, and data management systems that allow specialized access separately for research and for education and public outreach. Private, non-Federal funding

provided long-lead-time items and technology development essential for mitigating early risks. The NSF and DOE support installation and commissioning together. Operations support has been requested from both agencies and will be augmented by negotiated non-Federal and international in-kind contributions. Pre-operations ramp-up activity began in FY 2019.

Also in FY 2019, AST's Mid-Scale Innovations Program (MSIP) supported 21 programs, with five-year project costs typically in the range of $3–10 million. A landmark result was obtained by the MSIP-supported Event Horizon Telescope (EHT), which was announced on April 10, 2019, in press conferences that generated intense interest and headlines throughout the world. The striking image of the supermassive black hole in the center of the galaxy M87 was years in the making and involved an international collaboration of over 200 scientists, engineers, and students. This image, and its conformance to Einstein's General Theory of Relativity, constitutes the strongest evidence to date for the existence of black holes in the universe. In addition to becoming a popular cultural phenomenon, the EHT was the subject of a dedicated hearing of the U.S. House of Representatives Committee on Science, Space and Technology, and the team and Principal Investigator (PI) have begun to receive awards for their efforts, including the newly created NSF Diamond Award given to the PI and the 2020 Breakthrough Prize in Fundamental Physics awarded to the team.

In FY 2019, a new NSF foundation-wide midscale initiative, the Mid-scale Research Infrastructure Program, held its first competition, where it awarded a $12.6 million grant to support the design and development of the next phase of the EHT, with improved instrumentation and eight new antennas to be added to the array. This Next Generation EHT will enable time-resolved imaging to provide the first movies of activity near the event horizons of black holes.

Damage to the Arecibo Observatory (AO) resulting from Hurricane Maria, which hit the island of Puerto Rico in September 2017, was assessed, and the most critical damage was repaired during FY 2018 and FY 2019. The observatory was closed for a short time but resumed operations within weeks, albeit with some systems still disabled. A 29-meter-long line feed for use at 430 megahertz was torn from its moorings above the antenna and plunged into the surface of the dish, while the lower sections of the dish were flooded with water. Fortunately, none of

the staff were injured. In the aftermath of the storm, the observatory was used as a command center for emergency activity in the surrounding countryside. Funds in the amount of $12.3 million for repairs to AO infrastructure and instrumentation were appropriated by Congress in FY 2018, and a comprehensive repair plan was approved in FY 2019 after a thorough merit review panel. AO also received a $19 million NASA grant in FY 2019 to observe and characterize potentially hazardous near-Earth objects, setting a record in 2019 for the most asteroids observed in a single year (more than 100) at the facility. AO also continued to be a critical facility in the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) NSF Physics Frontier Center, observing dozens of pulsars with the goal of detecting and studying very-low-frequency gravitational waves.

Division of Physics

The Division of Physics (PHY) continued to operate its Laser Interferometer Gravitational-Wave Observatory (LIGO), which underwent commissioning work during the first part of this calendar year in preparation for the third observational run (O3) that started in April 2019. After a very successful six months of operation, LIGO took an additional commissioning break during the month of October and started the second part of O3 on November 1. LIGO has released 49 trigger alerts so far in 2019, of which 35 are currently considered gravitational-wave events and 14 have been retracted.

Complementing LIGO, the Division of Physics, in partnership with AST, continued its funding of NANOGrav. NANOGrav uses large radio telescopes to study the arriving clocklike signals from over 70 rapidly spinning pulsars to search for deviations in the timing that could indicate the passage of a single gravitational wave through our galaxy or the presence of a stochastic background of many gravitational wave sources throughout the universe. A typical source of gravitational waves for NANOGrav would be a black hole pair with millions of times the mass of the Sun, in contrast to LIGO's tens of times, and the wave itself would have a period of several years.

For a description of the IceCube Neutrino Observatory, partially supported by PHY, see the Division of Polar Programs section below.

Division of Atmospheric and Geospace Sciences

During FY 2019, the Space Weather Operations, Research, and Mitigation (SWORM) Working Group under the Space Weather, Security, and Hazards (SWSH) subcommittee within the Committee for Homeland and National Security (CHNS) of the National Science and Technology Council (NSTC) issued a new a National Space Weather Strategy and Action Plan (NSW-SAP, found at *https://www.whitehouse.gov/wp-content/uploads/2019/03/National-Space-Weather-Strategy-and-Action-Plan-2019.pdf*). This new plan has three main objectives, the second of which requires agencies to "Develop and Disseminate Accurate and Timely Space Weather Characterization and Forecasts." The NSW-SAP, monitored by the SWORM subcommittee, encourages the NSF to support fundamental research linked to societal needs for space weather information and to work with other agencies, specifically to "Improve Observations and Modeling for Characterization and Forecasting." The NSF is fulfilling this goal through its science programs in the Atmospheric and Geospace Science Division (AGS), the Directorate for Mathematical and Physical Sciences (MPS), and the Directorate of Geosciences program Prediction and Resilience against Extreme Events (PREEVENTS). Additional support comes through interagency collaborations, such as the joint sponsoring of the Community Coordinated Modeling Center located at NASA's Goddard Space Flight Center and the NSF-DOE plasma partnership.

The NSF, through AGS and MPS participation, remained active in SWORM activities. Representatives from the NSF participated in the efforts that led to the release of the new NWS-SAP. In addition, NSF/AGS has a leading role in the efforts to improve the initial space weather benchmarks that were published in FY 2017. In FY 2019, this effort focused on supporting the evaluation of the space weather benchmarks developed in FY 2018. This work included supporting a team of scientists to gather input from the research and operations communities through a series of town halls culminating in the development of an evaluation report that was released to the community through a workshop in the fall of 2019. A final report will be developed and released in FY 2020.

The Geospace Section (GS) within AGS supported a wide variety of research programs in space science in FY 2019. These included the funding of advanced

radar systems to study the ionosphere and magnetosphere, ground-based optical equipment to study the aurora and airglow, partial support to ground-based solar telescopes and instruments, and a wide-ranging portfolio of basic research in space physics. Major GS-funded activities in FY 2019 included the Geospace Facilities (GF) program; the Space Weather Research (SWR) program; the Solar-Terrestrial Research (STR) program; the Coupling, Energetics, and Dynamics of Atmospheric Regions (CEDAR) program; and the Geospace Environment Modeling (GEM) program.

The Geospace Section runs the Faculty Development in Space Sciences (FDSS) Program to ensure the health and vitality of solar and space sciences within university teaching faculties; it offers five-year awards for the creation of new tenure-track faculty positions within the intellectual disciplines that compose the space sciences. In FY 2019, the GS conducted a new competition for FDSS positions that resulted in the creation of seven new faculty positions. While the selection was made in FY 2019, one of those positions was funded in the beginning of FY 2020.

In FY 2019, the GS supported four new CubeSat missions. Two missions were selected as part of the ongoing CubeSat-based small-satellite science missions for geospace and atmospheric research and education. The IMpulsive Phase Rapid Energetic Solar Spectrometer (IMPRESS) experiment is a CubeSat science mission to study hard x-ray emission from solar flares. The Climatology of Anthropogenic and Natural Very Low Frequency (VLF) wave Activity in Space (CANVAS) CubeSat will measure VLF wave energy that originates from lightning and ground-based transmitters and propagates to the outer reaches of Earth's magnetic field. Through a partnership with the Computer and Information Science and Engineering Directorate and the Engineering Directorate, AGS conducted an IdeasLab to support the Cross-cutting Initiative in CubeSat Innovations. This process led to support for two additional CubeSat missions. The Virtual Super-resolution Optics with Reconfigurable Swarms (VISORS) mission supports the use of constellations of CubeSats for space weather through designing, building, and operating three satellites that together form an ultraviolet telescope for observing the Sun. The Space Weather Atmospheric Reconfigurable Multiscale Experiment (SWARM-EX) project provides an important step in the advancement of designing and building CubeSat constellations for space weather.

In FY 2019, the GS continued to support the satellite-based Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE), which is now in its second implementation phase, AMPERE-II. AMPERE utilized the 66 networked satellites of the existing Iridium constellation to create a new facility for collecting geomagnetic field data. The AMPERE facility continued to provide the first-ever global observations of the electric currents that link Earth's magnetosphere and ionosphere and the first-ever continuous global observations for tracking geomagnetic storm-time dynamics. Geomagnetic storms occur when charged particles emitted by solar eruptions interact with Earth's magnetosphere. Large geomagnetic storms can cause major disruptions of power and high-frequency (HF) communications systems on the ground and degrade the accuracy of satellite-based navigation services. During FY 2019, the data collection for AMPERE continued and the data remained freely available to researchers.

Research facilities remained as the key component of GS efforts. The Geospace Facilities program in FY 2019 continued to enable basic research on the structure and dynamics of Earth's upper atmosphere. In particular, the CEDAR and GEM programs conducted research efforts utilizing these facilities. Throughout FY 2019, observations made by the Advanced Modular Incoherent-Scatter Radar (AMISR) at Poker Flat, Alaska, examined the ionospheric effects of auroral particle precipitation in three dimensions. AMISR is ideally situated to observe the properties of the ionosphere in the polar cap, a region that is characterized by high ionospheric variability that often causes disruption of important navigation and communication systems. In collaboration with the Division of Astronomy, the GS supervised a cooperative agreement with a consortium led by the University of Central Florida for the operation the radar facility at Arecibo. In addition, the NSF has made an award of $12 million to repair damages caused by Hurricane Maria.

In FY 2019, the AGS's Atmosphere Section (AS) continued to support the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC). The University Corporation for Atmospheric Research (UCAR) and its collaborator, Taiwan's National Space Organization, designed and built the COSMIC six-satellite constellation, which launched on April 14, 2006, with the support and assistance of the U.S. Air Force's Space Test Program. As this mission is well past its designed lifetime, only a limited number of GPS radio occultation

measurements were made and provided to the research community. The UCAR group also processes data for several radio occultation satellite missions, including KOMPSAT-5 and PAZ, which are used operationally. Support for this activity comes from NASA as well as NSF. The follow-on COSMIC 2 mission was launched by the USAF and will be operated through a collaboration between NOAA, the USAF, and Taiwan.

Office of Polar Programs

For FY 2019, the primary activities of the Office of Polar Programs (OPP) in ground-based space science and astronomy included continued full-scale observations at the U.S. Amundsen-Scott South Pole Station with the 10-meter off-axis radio South Pole Telescope (SPT); the battery of five small-aperture (26-centimeter) telescopes called the Small Polarimeter Upgrade for Degree Angular Scale Interferometer (SPUD) array; and another, stand-alone Background Imaging of Cosmic Extragalactic Polarization (BICEP3) telescope—a wide-field cryogenic refractor with a 55-centimeter aperture and fast optics that achieves an order-of-magnitude increase in throughput. These telescopes have a total of 5,120 detectors ("pixels") in their focal planes. Recent scientific results from the BICEP Collaboration include deep multi-frequency (95-, 150-, 220-, and 270-gigahertz) maps of degree-scale *B*-mode polarization that measure gravitational lensing and foregrounds to unprecedented precision. This project also produced the deepest-ever maps of CMB polarization at four different frequencies, or colors, of light. The constraints that BICEP telescopes have produced on primordial gravitational waves continue to improve, leading the way in probing models of inflation that operate near grand-unified theory (GUT) energy scales.

The SPT continued observations with the third-generation receiver SPT-3G, which has wide-field optics to measure the CMB polarization at high sensitivity with the total 15,234 detectors in its focal plane. Both the SPT and BICEP research groups are currently focusing on measurements of the CMB polarization anisotropy. They target measurements of the *B*-mode polarization where primordial gravitational waves should have their imprint, as well as on the *B*-mode signal caused by the gravitational lensing of the intrinsic CMB's *E*-mode polarization

signal. Polarization measurements on smaller angular scales measured with the SPT are being used to increase the precision of the CMB-lensing determination of projected mass maps of the sky.

The SPT-3G camera has three observing bands (centered at 95, 150, and 220 gigahertz) and represents a fundamental step forward in CMB polarization measurements. Recent SPT results for delensing the CMB polarization signal from gravitational effects of galaxy clusters are helping to form a better understanding of foregrounds at the degree-scale anisotropies in the CMB.

The IceCube Neutrino Observatory (ICNO, jointly operated at the South Pole by the NSF's Office of Polar Programs and Division of Physics) has now collected data for nine full years of operation from a complete array of 86 strings of optical photodetectors deployed in the ice under the South Pole Station in Antarctica at depths between 1.4 and 2.4 kilometers. The existing detector is capable of observing cosmogenic neutrinos with energies of 100 gigaelectronvolts (GeV) to 10 petaelectronvolts (PeV).

"NSF is excited about the current upgrade to the IceCube observatory, as well as the long-term plans for IceCube-Gen2," said NSF Director France Córdova in her video message remarks to the International Cosmic Ray Conference held in Madison, Wisconsin, in July 2019. "And we are excited about our plans to invest in midscale research infrastructure that will enhance a wide range of research facilities."

The ICNO has produced the world's best limit on the flux of cosmogenic neutrinos, which places very strong constraints on the sources of ultra-high-energy cosmic rays. The petaelectronvolt neutrinos observed by IceCube have a thousand times the energy of the highest-energy neutrinos produced with Earthbound accelerators and a billion times the energy of the neutrinos detected from supernova SN1987 in the Large Magellanic Cloud, the only neutrinos that had been detected on Earth from outside the solar system prior to IceCube's breakthrough. However, the most surprising property of these cosmic neutrinos is their large flux rather than their high energy or their origination outside our galaxy.

In 2013, observations made by researchers using the IceCube detector at the South Pole and verified by ground- and space-based telescopes have produced the first evidence of one source of high-energy cosmic neutrinos. These ghostly

subatomic particles can travel unhindered for billions of light-years, journeying to Earth from some of the most extreme environments in the universe. In 2017, the ICNO revealed an answer to a century-old quest for the origin of high-energy cosmic rays, tracing the path of a very-high-energy neutrino back to a previously known but little-studied blazar—the nucleus of a giant galaxy that fires off particles in massive jets of elementary particles, powered by a supermassive black hole at its core.

The ICNO results opened a new window to the universe, providing novel insights into the engines that power active galactic nuclei and generate high-energy cosmic rays, gamma-ray bursts, and other violent and energetic astrophysical processes. ICNO's exploration of scientific frontiers has already changed and expanded our understanding of the universe. These achievements show neutrinos to be a key cosmic messenger, revealing an unobstructed view of the universe at wavelengths where it is opaque to light and radio emissions, including x-rays and gamma rays.

The NSF's Office of Polar Programs also supports NASA's Long Duration Balloon (LDB) Program in the Antarctic. McMurdo Station provides the necessary logistics for astrophysics payload assembly and final testing and then helps launch the balloons and support payload recovery after the flights in various regions of the Antarctic continent. A total of 55 LDB science payloads were successfully launched from McMurdo since the first interagency Memorandum of Understanding was signed in August 1988.

Department of State

DOS

The Department of State (DOS) carries out diplomatic and public diplomacy efforts to strengthen United States leadership in space exploration, applications, and commercialization by increasing understanding of, and support for, U.S. national space policies and programs and to encourage the foreign use of U.S. space capabilities, systems, and services. The Office of Space and Advanced Technology within the Bureau of Oceans and International Environmental and Scientific Affairs (OES/SAT) directly supports these missions through the negotiation of bilateral and multilateral engagement with partner countries and by leading U.S. participation in numerous international space and technological activities and international organizations.

Multilateral Activities

The Department of State and U.S. Department of Commerce's space offices organized and led the first Space Enterprise Summit in Washington, DC, during July 2019. Over 500 participants from all over the world attended the Summit. The Summit provided an opportunity for senior representatives from government, industry, and space organizations to strengthen international cooperative efforts relating to the administration's high-priority issues, such as long-term sustainability in space and the development and utilization of outer space. The OES Deputy Assistant Secretary for Science moderated several of the Summit's panel discussions on the key space economy issues prompted by foreign ministry officials and CEOs.

OES/SAT successfully led efforts in June to ensure the adoption of 21 Long-Term Sustainability (LTS) guidelines at the United Nations (UN) Committee on the Peaceful Uses of Outer Space (COPUOS) in Vienna. These guidelines largely reflect current U.S. Government and industry best practices and highlight our commitment to the safety and accessibility of outer space. OES/SAT then worked with other like-minded nations to highlight the 21 LTS guidelines at the 74th UN General Assembly (UNGA) in the fall of 2019. Working with NASA Deputy Administrator James Morhard, Executive Secretary of the National Space Council Scott Pace, the UN Office for Outer Space Affairs (UNOOSA), the Permanent Mission of Italy, and the Government of Zambia, OES/SAT leadership co-organized with UNOOSA the first-ever outer space–related side event at UNGA on September 23, 2019, called "Bringing the Benefits of Space to Everyone, Everywhere: The UN and the Private Sector." The event was intended to showcase how the UN is building an exciting partnership with the international private space sector to bring the benefits of space to everyone, everywhere. Also, OES/SAT met in Vienna several months before the UNGA event to highlight notable developments in the U.S. National Space Policy. OES/SAT discussed efforts to enhance the sustainability of space activities and the importance of U.S. leadership in promoting international space cooperation as well as fostering best practices for outer space activities to ensure a transparent and international framework under which governments and industry may operate.

OES/SAT successfully led U.S. participation in the 25th Asia-Pacific Regional Space Agency Forum (APRSAF) the week of October 31, 2018, promoting the administration's space policy goals of maintaining U.S. leadership in future space exploration plans, expanding space cooperation with nations in the Asia-Pacific region, and raising the visibility of U.S. industry in space exploration. The U.S. delegation, which consisted of Government, nongovernmental organizations (NGOs), and private-sector representatives, made progress in all these areas. The U.S. side also worked closely with Japan to promote civil and commercial space activities in the Asia-Pacific region.

In September 2019, OES/SAT advanced U.S. leadership and cooperation in planetary defense by participating in the International Asteroid Warning Network (IAWN) and Space Mission Planning Advisory Group (SMPAG) meetings in

Garching, Germany, to discuss issues concerning near-Earth object detection, tracking, intervention, and scientific discovery. The meeting brought together interested member states and private-sector representatives, including representatives from Avio International (Italy), Virgin Galactic (United States), and Maxar Technologies (United States), to highlight the value of space programs and activities and the importance of the commercial space sector.

Working-level discussions with the EU on GNSS also continued in FY 2019 through working groups formed by the 2004 U.S.-EU GPS-Galileo Cooperation Agreement, administered for the United States by OES/SAT. The working group on next-generation GNSS applications and its three subgroups, Service Evolution, Resiliency, and Service Provision Coordination, along with the working group on Trade and Civil Applications, were supported by OES/SAT representatives.

Science Envoy for Space

Since the summer of 2018, OES/SAT managed several highly productive overseas trips for the Department's first Space Envoy, Charles Bolden, Jr.—former NASA Administrator, Space Shuttle commander, and astronaut—to promote U.S. leadership in space exploration and the commercialization of space. In March 2019, OES/SAT led Bolden's visit to Paris, France, and Bangalore and New Delhi, India, and in June 2019, the team visited Hanoi and Ho Chi Minh City, Vietnam, and Kuala Lumpur and Penang, Malaysia. In India, OES/SAT coordinated with public diplomacy officers from the embassies of all of these countries to have Envoy Bolden's engagement with young engineers and law students covered extensively by media outlets with a combined reach in excess of 60 million people. A significant outcome of this trip was Envoy Bolden's meetings with the Indian Space Research Organization to open significant commercial opportunities for U.S. space-related businesses. As the guest of honor for Embassy Hanoi's Independence Day event, Envoy Bolden delivered remarks regarding the 50th anniversary of the Apollo 11 Moon landing and U.S.-Vietnam relations through his lens as a Vietnam War veteran. He met with the Director General of the Vietnam National Space Center, as well as the Minister of Science and Technology. The Minister expressed interest in signing a bilateral Space Framework Agreement with the United States during

President Nguyen Phu Trong's February visit to Washington. Envoy Bolden delivered space presentations for thousands of students and faculty in numerous universities and venues throughout Vietnam. During a day trip to Kuala Lumpur, Bolden spoke at a public event featuring the Minister of Energy, Science, Technology, Environment, and Climate Change, and he met with Malaysian Space Agency representatives at the planetarium. In Penang, the American Chamber of Commerce Penang Chapter hosted a science and technology reception, which allowed Envoy Bolden to meet with U.S. companies and Malaysian vendors. Envoy Bolden bylined an OES/SAT-drafted State Department media blog about the envoy's world tour as U.S. Science Envoy for Space.

50th Anniversary Moon Landing Events

In coordination with George Washington University's Space Policy Institute, the State Department public affairs division and OES/SAT organized a panel discussion featuring Envoy Bolden and Apollo 11 astronauts Michael Collins and Buzz Aldrin. This public event commemorated the 50th anniversary of the Apollo 11 Moon landing with opening remarks from Economics Bureau Undersecretary Keith Krach about space exploration and the space economy. During Envoy Bolden's trip to Malaysia, OES/SAT collaborated with a local film crew to make a short documentary featuring Envoy Bolden and his one-year stint as space envoy in front of Kuala Lumpur's Petronas Twin Towers. The film included a personal message about the 50th anniversary of the Apollo 11 Moon landing. State public affairs and OES/SAT released a blog and the film on social media. OES/SAT authored a widely distributed cable that proved successful in convincing a multitude of embassies to celebrate July 4 with a space theme to commemorate the 50th anniversary of the Apollo 11 Moon landing. As a result, most of the embassies and consulates featured space-themed decorations, films, and guest speakers, including former astronauts, and captured the festivities with numerous photos on social media. Many diplomatic posts were so inspired that they held numerous space-related events throughout the year and have continued some of these events as an effort to stimulate STEM outreach activities.

Agreements

Throughout 2019, OES/SAT continuously led the interagency coordination efforts for the clearance and authorization of over 60 international binding space agreements from NOAA, NASA, and USGS under the C175 (congressionally mandated) process. Most of the agreements' requests come from NASA for implementing arrangements with their main space agency counterparts from Italy, India, Japan, France, Germany Argentina, Brazil, and the European Space Agency, but they also included several new space partners this fiscal year from Armenia, Israel, Indonesia, and United Arab Emirates government agencies and commercial space organizations. During FY 2019, some of the most well-known space agreements were renewed through this C175 process: the Search and Rescue Satellite-Aided Tracking (COSPAS-SARSAT), Hubble, Chandrayaan-2, SpaceIL (first privately funded and first Israeli Moon lander), and James Webb Space Telescope agreements. OES/SAT led the international negotiations for the renewal and renegotiation of COSPAS-SARSAT, the more-than-50-year-old intergovernmental, humanitarian cooperative of 45 nations and agencies dedicated to search and rescue.

International Astronautical Congress

The 70th International Astronautical Congress (IAC) took place in Washington, DC, the week of October 21–25 (see *https://www.iac2019.org/*), and to inaugurate the first official day, OES/SAT led a high-level VIP reception for over 300 industry and government leaders in the space sector from more than 30 countries. The event, which featured remarks by NASA Administrator James Bridenstine, former OES Senior Advisor Jon Harrison, Assistant Secretary of State for Economic and Business Affairs Manisha Singh, CEO of Lockheed Martin Marilyn Hewson, and American Institute of Aeronautics and Astronautics (AIAA) President John Langford, highlighted the administration's priorities for the commercialization of space, a return to the Moon, and venturing onward to Mars. OES/SAT represented State on the IAC Local Organizing Committee for the full year prior to the event and provided valuable foreign policy perspectives and input that helped shape the weeklong event. OES Deputy Assistant Secretary for Science held several meetings

with CEOs from several foreign and domestic space industries on the margins to promote commercial space opportunities internationally. OES/SAT coordinated with State's Consular Affairs and embassies to handle visa-processing concerns for many of the 10,000 foreign guests. OES/SAT worked closely with State, NASA, and other press representatives to write media notes and several tweets that were broadcast once a week leading up to the event. Several hundred local school children were engaged and supported by OES/SAT in multiple hands-on STEM activities presented by NASA, space industry, and private partnership organizations on the sides of the conference.

Bilateral Engagement

On April 4, 2019, OES/SAT conducted a successful first U.S.-Indonesia Civil Space Dialogue that focused on space applications such as Earth observation, satellite navigation, and civil maritime domain awareness. The Executive Secretary of the National Space Council, Dr. Scott Pace, cochaired the session, addressing the Presidential space directives and the review of export control regulation. This dialogue will further our U.S. long-term foreign policy strategy and objectives as articulated in the U.S. National Space Policy and the recent Asia Reassurance Initiative Act (ARIA) and plays a vital role in making Indonesia a key partner in the broader U.S. economic and national security outreach in the region. During late summer, OES Senior Advisor Jon Harrison and Director of Space Commerce Kevin O'Connell led the U.S. delegation to the second U.S.-Thailand Civil Space Dialogue in Bangkok. Through our emphasis on the emerging challenges and opportunities in the space sector, the U.S. delegation was able to break new ground with the entire Thai government. Furthermore, by welcoming participants from industry, nonprofit organizations, academia, and civil society on the second day, the delegation was able to broaden the conversation on economic and scientific opportunities for space cooperation.

Another important bilateral space dialogue that the Department of State facilitated during 2019 was with the European Commission (EC), whose space agenda continues to expand. On June 12, 2019, the European Commission hosted the tenth meeting of the U.S.-EU Dialogue on Space Cooperation at the European

Global Navigation Satellite Systems (GNSS) Agency Headquarters in Prague, Czech Republic. Although this bilateral discussion is to take place every year, 16 months had passed since the previous meeting in Washington, DC, on January 18, 2018. Twenty U.S. officials traveled to Prague for this meeting, including representatives from the departments of Commerce (NOAA), Defense, Interior (USGS), and State. OES/SAT coordinated the interagency participation, presentations, and policy goals for the U.S. delegation, led by OES and the Arms Control, Verification, and Compliance Deputy Assistant Secretaries. The European side was led by the special envoy on space from the European External Action Service and the EC's Directorate General for Internal Market, Industry, Entrepreneurship and Small Medium Enterprise. The civil dimension of the dialogue was dominated by detailed discussions on US-EU cooperation in two major European space systems: the Galileo program on GNSS and the Copernicus Earth observation program. Both of those programs continue to receive growing financial investments from the European Union. This year, the Commission's space request to the European Parliament's Multi-year Financial Framework (2021–27) was 16 billion euros. The 2019 U.S.-EU Space Dialogue also included topics such as space security; space policy and governance; space situational awareness; space traffic management; space policy developments on commercial space; joint implementation of the COPUOS Long Term Sustainability Guidelines; and collaboration in space fora such as the Group on Earth Observations, Committee on Earth Observations, Consultative Group on Meteorological Satellites, International Committee on GNSS, and COPUOS. The next meeting of this dialogue will take place in Washington in early 2020.

OES/SAT met during the summer of 2019 with interagency and foreign embassy counterparts for Kazakhstan, Ukraine, and Israel to promote President Donald Trump's space directives on U.S. leadership in space exploration and the commercialization of space. To further joint space activities under the U.S.-Ukraine Space Framework (SFA) agreement, OES/SAT was successful in generating more U.S. Government space agency involvement to justify the SFA's renewal. When Pakistan announced its plans to select and fly an astronaut by 2022, OES/SAT proactively worked with U.S. Embassy Islamabad's science officers through Envoy Bolden and with the U.S. space industries to encourage Pakistan to utilize

American companies to achieve its space objectives and to market certain aspects of human and robotic commercial spaceflight.

Commercialization of Space

Throughout the year, OES/SAT has promoted American leadership in outer space by carrying out diplomatic efforts domestically and internationally to strengthen our U.S. national space policies, programs, and Presidential directives. OES/SAT has drafted policy and briefing materials for State's principals and represented the State Department at all of the National Space Council meetings. OES/SAT regularly meets with numerous private-sector space company officials and has authored a soon-to-be released, all-diplomatic-posts cable on State's activities relating to the international and domestic expansion of space commercialization.

Department of Energy

DOE

The Department of Energy (DOE) participates in the national effort to further U.S. interests in space. Organizations within DOE that provide this capability are the Department of Energy's National Nuclear Security Administration (NNSA), Office of Science (SC), and Office of Nuclear Energy (NE). In FY 2019, DOE participated in the National Space Council and established an internal Space Coordination Working Group to facilitate these activities, highlights of which are summarized below.

Mission Contributions Within the National Nuclear Security Administration

In 2019, the NNSA supported the national plan to defend the planet from potentially hazardous near-Earth objects, conducted numerous Strategic Partnership Projects that use NNSA technical capabilities to support civil space missions, and continued to provide dual-purpose sensor and satellite development/deployment work with applications to national security and civil space programs. In addition, NNSA continues to provide space weather information. Each of these activities is described below.

Planetary Defense: NNSA worked with NASA and the interagency community relative to U.S. interests in space. NNSA participated in the Detecting and Mitigating the Impact of Earth-Bound Near-Earth Objects (DAMIEN) initiative and, as part of the Mission Executive Council initiative, developed a strategic framework for space protection, primarily focusing on satellites. The DAMIEN initiative developed the June 2018 National Near-Earth Object Preparedness Strategy and

Action Plan to help improve our Nation's preparedness to address the hazard of near-Earth object (NEO) impacts. This plan had two strategic goals pertaining to NNSA: to improve NEO modeling, predictions, and information integration, and to develop technologies for NEO deflection and disruption missions. The Interagency Agreement regarding planetary defense between NNSA and NASA fulfilled the actions of these two strategic goals. NNSA indirectly supports the other strategic goals of enhancing deflection, tracking and characterization capabilities; increasing international cooperation; and strengthening impact emergency preparedness.

NASA leverages NNSA-unique engineering, scientific, and high-performance computing capabilities to analyze asteroids. This work helps to develop and exercise capabilities that are relevant to the weapons program, including two- and three-dimensional simulations, weapon effects, system engineering, and weapon component design.

Under the NNSA-NASA interagency agreement, the two agencies collaborated on the following:

- Characterized the potentially hazardous asteroid target sets, defined mission requirements, and identified capability gaps.
- Helped define design requirements, including instruments for future reconnaissance missions to support asteroid characterizations.
- Examined the effects of either a kinetic impactor and/or a nuclear detonation, either at the surface or at a standoff distance from a model asteroid, using simulations from petascale computers at the National Laboratories.
- Defined additional development and system engineering requirements addressing technical gaps such as arming, fusing, and firing a deflection device.
- Participated in planetary defense tabletop exercises and technical interchange meetings.
- Advised on risk-assessment analysis and the effectiveness of mitigation approaches.

Strategic Partnership Projects: NNSA supported Strategic Partnership Projects in FY 2019, funded by NASA, with the following capabilities:

- Provided metrology support with calibration on standards and measuring test equipment supporting metrology areas at NASA's White Sands Test Facility.

- Monitored satellite visible-light sensor data for bolide occurrences worldwide and generating reports detailing bolide parameters.
- Modeled asteroid entry, airburst, and surface impact effects.
- Enabled joint exploration of sounding rocket technologies at NASA's test ranges.

Radioisotope Power Systems (RPS) Launch: NNSA, NE, and NASA worked collaboratively during the preparation for and execution of the RPS launch at Kennedy Space Center (KSC). This work is complementary to the work done by NE.

- During the preparation phase, NNSA, NE, and NASA reviewed and updated procedures and conducted training, drills, and exercises with the state, Tribal, and local emergency management organizations and agencies. NNSA, NE, and NASA worked together to validate the ability to manage the consequences of a launch anomaly that may result in an uncontrolled release of radiological materials into the atmosphere and surrounding environment.
- During the execution phase, NNSA will stage technical specialists and sensors in the vicinity of the launch site to respond immediately in the unlikely event of a launch anomaly. NNSA personnel will be assigned to the KSC Primary Agency Representative Management Group, Radiological Control Center, and Joint Information Center to provide real-time radiological consequence assessment and risk communication support to KSC. Should the radiological consequences of a launch anomaly adversely impact the environment surrounding KSC, an NNSA-led Federal Radiological Monitoring and Assessment Center would be established off-site to provide technical advice and assistance to state and local incident management on characterizing and mitigating those consequences on the public and the environment.

NASA's Environmental Continuous Air Monitors: NNSA maintained the NASA-owned Environmental Continuous Air Monitors for deployment around the launch site in advance of a launch to provide indication of a release of radiological materials, should one occur. NASA has agreed to lend these sensors in support of NNSA's nuclear incident response mission when those devices are not being used for mission launch support. These devices have been upgraded to provide

real-time associated data telemetry systems and will be interoperable with NNSA's existing data telemetry capability.

Global Nuclear Monitoring: NNSA builds the Nation's operational sensors to monitor the entire planet from space in order to detect and report surface, atmospheric, or space nuclear detonations. NNSA provides much of the Nation's capability to detect, report, locate, and identify nuclear explosions using orbiting satellites. NNSA develops, builds, and delivers these satellite payloads to meet interagency performance and schedule commitments. NNSA also provides launch and on-orbit operational support for the current generation of the U.S. Nuclear Detonation Detection System (USNDS).

Since the 1960s, beginning with the Vela satellite program, NNSA and its predecessors have provided the underlying science and technology capability for space-based detection of foreign nuclear weapon detonations to meet Test Ban Treaty monitoring needs. This fiscal year, NNSA continued full-scale production and delivery of sensor payloads as needed to meet national security requirements. To ensure that the technologies and capabilities developed for the program support stakeholder needs, NNSA actively engaged in intergovernmental working groups to reduce duplication of effort, refine user requirements, and improve the quality of relevant technologies across funding agencies.

The NNSA weapons laboratories—Los Alamos National Laboratory (LANL), Sandia National Laboratories (SNL), and Lawrence Livermore National Laboratory (LLNL)—supply the science, technology, and engineering required for USNDS. LANL and SNL lead the production of sensor-laden payloads, and LLNL contributes to the end-to-end modeling of USNDS. These laboratories have a unique and comprehensive understanding of nuclear weapons, as well as the observables associated with nuclear detonations and the propagation of signals to sensors. Moreover, these laboratories have extensive capabilities in the design, construction, calibration, deployment, and operation of satellite-based instruments, along with detailed modeling and analysis. To support continuous global monitoring, the operations communities routinely receive analysis, insights, and computer codes based on this research.

Two payload suites built at the NNSA laboratories accomplished the nuclear detonation reporting mission: the Global Burst Detector (GBD) and the Space

and Atmospheric Burst Reporting System (SABRS). The GBD is hosted on all GPS satellites, and SABRS is carried on satellite hosts in geosynchronous orbit. In order to maintain a vital capability to design and implement these systems, NNSA supported demonstration-validation payloads both to explore new technologies and new sensing modalities and to increase the Technology Readiness Level for parts that might be used in future payload designs.

Research Sponsored by the DOE Office of Science

In FY 2019, SC supported several activities that contribute to a broad range of space interests. These activities included SC fundamental research that is of mutual interest to NASA and SC, collaborative research efforts with NASA, and the operation of SC scientific facilities that are available to NASA and the broader scientific community for space-related research.

SC supports frontier plasma science research that contributes to SC-NASA mutual interests in the knowledge of heliospheric and astrophysical systems. Some of the research supported by SC's Office of Fusion Energy Sciences (FES) enables the development of a comprehensive understanding of heliospheric and astrophysical magnetized plasma processes, including magnetic reconnection, particle energization, and turbulent cascade processes in the solar corona and Earth's magnetosphere; Alfvén wave acceleration of auroral electrons; eruptive instabilities leading to solar flares and coronal mass ejections; plasmoid instability in fast reconnection; collisional and collisionless shock; magneto rotational instability in generating turbulence in accretion disks; and dynamo processes creating planetary/galactic magnetic field structures.

Specific examples of FES-supported activities in FY 2019 included 1) the Large Plasma Device at the Basic Plasma Science Facility at the University of California, Los Angeles, which enabled controlled studies of Alfvén waves that carry energy and momentum from the Sun to Earth and throughout the universe; 2) the Magnetic Reconnection Experiment (MRX) at DOE's Princeton Plasma Physics Laboratory (PPPL), which permitted laboratory studies of magnetic reconnection and particle-energization processes in the solar corona and Earth's magnetosphere; 3) the Big Red Plasma Ball and Madison Symmetric Torus experiments at the

Wisconsin Plasma Physics Laboratory (WiPPL) at the University of Wisconsin–Madison, which allowed comprehensive experiments, isolating the key effects of magnetic reconnection, dynamo, turbulence, and particle-energization processes with high fidelity; and 4) the Max-Planck-Princeton Center for Plasma Physics, which specifically explored the application of plasma science to solar and astrophysical problems and their connections to fusion science. Both WiPPL and MRX data have been used to validate and compare with observations from the NASA Magnetospheric Multiscale Mission.

In addition, FES sponsored unmagnetized plasma and high-energy-density laboratory plasma research, focusing on areas such as increased understanding of the role of dusty plasmas in planetary rings and interstellar media. FES also performed laboratory studies of ice dusty plasma to understand the scientific connections between Saturn's rings and Earth's high-altitude noctilucent clouds, as well as to understand the origin of cosmic magnetic fields, the study of nuclear astrophysics, and the properties of warm dense matter similar to that found in planetary cores (e.g., "diamond rain" in the interior of icy giant planets like Uranus and Neptune). Recently, SC charged the Fusion Energy Sciences Advisory Committee to conduct a long-range planning activity for the entire program, including fusion and discovery plasma science. The first part of this activity consists of community-organized meetings led by the American Physical Society Division of Plasma Physics, including members of the NASA research community.

SC also funds the development of experimental techniques and instrumentation for use on NASA space missions to study fundamental physics and investigate high-priority national science objectives through SC's Office of High Energy Physics (HEP). Examples of these efforts include the Alpha Magnetic Spectrometer (AMS) and the Fermi Gamma-ray Space Telescope (FGST). The AMS is a particle physics experiment supported by HEP and international partners, who designed and built the AMS-02 detector and associated systems. Launched on Space Shuttle Endeavour on Space Transportation System (STS) mission STS-134 in May 2011 and mounted on the International Space Station (ISS), AMS searches for various types of unusual matter in the cosmos through its exquisite accuracy in the measurement of cosmic rays. AMS science goals include a search for evidence of dark matter and cosmic domains of antimatter, as well as for novel features in

cosmic-ray spectra. A Memorandum of Understanding (MOU) signed between HEP and NASA defined NASA's responsibilities to include provision of power, data handling, and other services on the ISS, while HEP's responsibilities include experimental operations and data analysis. As of 2019, more than 120 billion cosmic-ray events have been collected, with data-taking continuing to enable precision measurements of the abundance and spectra of cosmic-ray antimatter, which can give information about dark matter, and to search for heavy antimatter. Recent results include precision measurements based on 1.9 million high-energy cosmic-ray positrons. The positron production at low energies is due to collisions with cosmic rays. At high energies, the data show that positrons originate either from dark matter annihilation or other astrophysical sources.

The Large Area Telescope (LAT), the primary instrument on NASA's FGST, is a particle physics detector in space whose purpose is to study the gamma-ray sky for high-energy acceleration mechanisms generated by supermassive black holes and supernovae and to search for dark matter. It does a complete survey of the entire sky in high-energy gamma rays every three hours and enables searches for transient phenomena over a wide range of timescales. HEP managed the LAT fabrication and now carries out critical roles at the LAT Instrument Science Operations Center. In FY 2019, the LAT collaboration published competitive limits on dark matter annihilation from observations of the nearby M31 and M33 galaxies. The collaboration also published a search for velocity-dependent (p-wave) annihilation of dark matter from LAT observations of the center of the Milky Way.

SC also made crucial contributions to the European Space Agency–NASA Planck Cosmic Microwave Background (CMB) mission, which took data from 2009 to 2013. Planck measures the CMB, which allows studies of the inflationary epoch in the early universe as well as dark energy, dark matter, and neutrino properties. A NASA and DOE MOU enabled dedicated DOE National Energy Research Supercomputing Center (NERSC) supercomputing resources for the Planck mission. NERSC resources have made it possible to understand and mitigate systematic effects to the exquisite precision needed for the data analysis. This enabled the Planck team to conduct the most precise CMB data analysis ever achieved, providing 20 to 30 percent lower noise and systematic errors, leading to better science results. The resources provided by NERSC are especially important since the science available

from the all-sky and high-frequency CMB observations in space is not likely to be surpassed for at least a decade. The head of the Computational Cosmology Center at DOE's Lawrence Berkeley National Laboratory received the NASA Exceptional Public Achievement Medal for leading the Planck efforts at NERSC.

SC also engaged in many collaborative research efforts with NASA through SC's Office of Biological and Environmental Research in the areas of atmospheric science and terrestrial ecology. During FY 2019, SC's Atmospheric Radiation Measurement Research Facility (ARM) and Terrestrial Ecosystem Science (TES) activities supported measurements of atmospheric trace gases in Oklahoma to improve understanding of the influence of atmospheric and terrestrial processes on atmospheric carbon dioxide concentrations. ARM provided support for ground-based measurements of carbon dioxide in Oklahoma as part of the Total Column Carbon Observing Network; these measurements are being used to validate NASA's Orbiting Carbon Observatory-2 (OCO-2) satellite. SC's ARM user facility supported the launch of dedicated radiosonde observations during satellite over-passes at three sites (Southern Great Plains, Oklahoma; Graciosa Island, Azores; and Barrow, Alaska) to obtain profiles of temperature and moisture for the validation of algorithms for the Cross-track Infrared Sounder and Advanced Technology Microwave Sounder on the Suomi National Polar-orbiting Partnership satellite and Joint Polar Satellite System satellites.

SC's ARM user facility also supported campaigns at the ARM Oklahoma site for test deployments and validation of two new NASA-funded instruments—a differential absorption radar developed by the NASA Jet Propulsion Laboratory to retrieve water vapor within clouds and the balloon-borne transverse electromagnetic measurement instrument, which is supported by NASA's Planetary Instrument Concepts for the Advancement of Solar System Observations program.

The SC TES activity supports the Next Generation Ecosystem Experiment (NGEE)-Arctic, which has collaborated with the NASA Arctic-Boreal Vulnerability Experiment study to couple real-time ground-based and airborne-based measurements of soil moisture, temperature, carbon dioxide, and methane flux over Barrow and Council, Alaska. A Memorandum of Agreement between the two activities enables the leveraging of complementary expertise, such as the generation of high-resolution lidar and elevation data products, as well as including

representatives on each project's science team to provide coordination of data and modeling efforts. NASA's G-LiHT airborne imager is being used to characterize tropical forest dynamics across a range of edaphic, climatic, and land-use gradients (both prior to and following Hurricane Maria) in Puerto Rico to support SC's NGEE-Tropics activity. Through interagency agreements, SC's Atmospheric System Research activity also supported collaboration with NASA scientists on studies using ARM and NASA observations to investigate aerosol and cloud processes and their role in Earth's energy balance.

SC has been working with NASA in several areas to help support NASA's mission interests, providing scientific user facilities, including particle accelerators and ion beams, for biological and electronic systems radiation studies. The NASA Space Radiation Laboratory (NSRL), a leading facility for radiobiology studies in the United States, was established at DOE's Brookhaven National Laboratory (BNL) to study the effects of cosmic radiation exposure on astronauts. The NSRL uses beams of heavy ions extracted from BNL's Booster accelerator (these are also produced for SC's Relativistic Heavy Ion Collider [RHIC] facility) to increase our understanding of the link between ionizing radiation and cell damage, leading to safer space exploration for astronauts. NASA and SC's Office of Nuclear Physics (NP) have collaborated on upgrades of mutual benefit, most recently enhancing the jointly funded upgrades to the Electron Beam Ion Source at RHIC to provide increased ion-beam intensities for gaseous elements, including light ions such as hydrogen and helium. SC also supports fundamental research on nuclear reactions of astrophysical interest, contributing to SC-NASA mutual interests in the knowledge of stellar evolution, neutron star mergers, gamma-ray bursts, and the composition of interstellar space.

A 2018 National Academy of Sciences (NAS) study supported by SC, NASA, and other agency stakeholders, *Testing at the Speed of Light: The State of U.S. Electronic Parts Space Radiation Testing Infrastructure*, focused on a comprehensive assessment of the future needs of the electronics space-radiation effects testing program in the United States. Electronics space-radiation effects testing that is necessary for NASA mission assurance occurs at two DOE accelerator facilities, BNL and the Lawrence Berkeley National Laboratory's 88-inch cyclotron. NP and NASA have an interagency agreement for NASA to provide funding for the

88-inch cyclotron operations to conduct electronics testing. SC and other stakeholders are initiating research and development that could lead to enhanced capabilities for radiation effects testing at the 88-inch cyclotron.

Capabilities Developed via DOE Office of Nuclear Energy Sponsorship

NE supports NASA's planetary science and human exploration programs by working with NNSA to maintain capabilities to develop, produce, and deliver Radioisotope Power Systems (RPS) for Federal user agencies, such as NASA. The RPS infrastructure capabilities, funded by NASA and managed by NE, support NE's production of RPS for current space mission applications. NE and its predecessors have provided RPS that have safely powered more than two dozen space exploration and national security missions for over five decades. RPS convert the heat from the natural radioactive decay of plutonium (Pu)-238 into electricity. RPS reliably operate for decades under the harsh conditions encountered in deep space or on the surfaces of other planets where solar energy or stored energy devices are ineffective or impossible to use. Radioisotope Thermoelectric Generators are flight-proven RPS that provide power and heat to a spacecraft.

In FY 2019, through Interagency Agreements with NASA and Strategic Partnership Projects with the DOE National Laboratories, NE continued to support the next RPS-powered mission, Mars 2020, completing a number of major milestones. As part of the preparations for Mars 2020, a trailblazer activity at NASA- KSC was successfully conducted in January 2019. This was a large, multi-organization dry run of all procedures that involved handling a multi-mission radioisotope thermoelectric generator (MMRTG) with Idaho National Laboratory, the Jet Propulsion Laboratory, United Launch Alliance, NASA-KSC, security organizations, and health physics organizations. The flight MMRTG F-2 was successfully fueled in August 2019 and produced 120 W_e at 28 V (spec. power 110 W_e). Acceptance testing was under way at year's end with vibrational testing finished in September 2019. Additionally, NE continued to work with Sandia National Laboratory to prepare the Mars 2020 Safety Analysis Report, which was successfully submitted in August 2019 to NASA.

With NASA funding support, NE continues to invest in current RPS production infrastructure through an approach called constant-rate production (CRP). The CRP strategy addresses NASA's needs by positioning the RPS infrastructure to support a level of sustained production of certain components. This strategy focuses on long-lead-time components that would support the production of Pu-238 heat-source material, heat source (fueled clads), specialized materials that support the production of heat sources (iridium-clad vent sets and carbon-bonded carbon-fiber sets), and the placement of the heat sources into a stable configuration for storage (up to several years). The CRP goals are as follows:

1. Producing 1,500 grams of heat-source Pu-238 oxide annually by FY 2025.
2. Manufacturing 10–15 fueled clads a year by FY 2020.

The outcome of the CRP strategy is an underlying base of shelf-ready, flight-quality components that are readily available once NASA selects a nuclear-enabled mission, thus reducing overall mission schedule risks. This approach also has a net positive effect on the NASA mission of reducing the mission-specific cost for utilizing RPS because the support for CRP would eliminate the costly, cyclical approach in standing up and standing down fuel production activities. DOE national laboratories have already demonstrated results toward achieving the CRP goals. Since 2015, Oak Ridge National Laboratory (ORNL) has produced approximately 350 grams of heat-source plutonium-238 oxide over three campaigns at the High Flux Isotope Reactor (HFIR) and completed a fourth campaign in the fall of 2019 to provide another 220 grams of material. Efforts are under way to optimize the HFIR beryllium reflector for Pu-238 production and to certify the Advanced Test Reactor (ATR) at Idaho National Laboratory (INL) for production in the early 2020s, utilizing a standard neptunium target. The HFIR suffered a fuel anomaly early in FY 2019, which had the reactor down for the entire year. However, readiness reviews were successfully concluded by both ORNL and DOE by the fourth quarter of FY 2019 for the reactor to start up in FY 2020. The target qualification effort for ATR is under way, with placement of a neptunium target into a medium I-position (I-7); the target will remain there for several cycles. Efforts in FY 2020 for the INL will revolve around qualifying other positions in ATR for Pu-238 production, such as A, B, H, and flux traps.

NE, through the DOE national laboratories, provided technical expertise, procurement coordination, and review planning and support to NASA in conducting basic and applied energy conversion research and development to advance state-of-the-art performance in heat-to-electrical-energy conversion. Both static and dynamic energy conversion projects are under way at this time; however, dynamic conversion, which can achieve higher efficiency, has not been developed to flightworthy status as yet. The goal of these investments is to provide higher conversion efficiency and improve mission performance over design life through robustness. Increased efficiency would benefit the program by extending the effective use of the Pu-238 supply. There are three development efforts currently under way that encompass both static and dynamic conversion systems: the enhanced multi-mission radioisotope thermoelectric generator, the next-generation radioisotope thermoelectric generator, and a small selection of dynamic generators (both Brayton and Stirling types).

A new approach to launch safety is being explored using safety documents framed around the technology employed rather than being mission-specific. The initial test case for this approach is using a documented safety analysis for the lightweight radioisotope heater unit. This has been released as part of an environmental assessment for their use going forward in the summer of 2019.

NE, through the DOE national laboratories, provides technical support for surface fission system development. Following the completion of the Kilopower Reactor Using Stirling Technology (KRUSTY) test in March 2018, NASA and DOE have begun to evaluate system concepts that can successfully meet the mission requirements for surface power needs on the Moon and Mars. NASA's Space Technology Mission Directorate (STMD) provided technical and performance requirements, including a target launch date of 2027. NASA's Glenn Research Center provided funding in FY 2019 to LANL to develop a detailed project plan, including an evaluation of current reactor technology options and a strategy for technology maturation and component fabrication, qualification, and acceptance testing. This work involves close collaboration with INL.

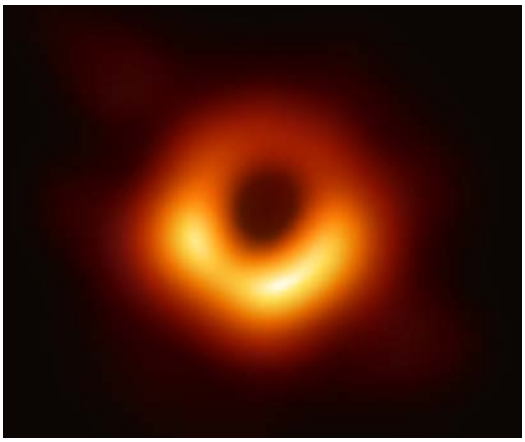
Finally, NE, through the DOE national laboratories, provides technical support for the Nuclear Thermal Propulsion (NTP) system development led and funded by NASA. NASA has renewed its efforts to design, develop, and deploy a nuclear

thermal propulsion system with the objective of demonstrating the feasibility of using NTP to support human missions to Mars. Congress has shown support for the technology development effort by funding an NTP flight demonstration that is scheduled to be completed by the mid-2020s. NASA's Marshall Space Flight Center provided funding in FY 2018 and FY 2019 to INL to continue efforts on NTP. The collaborative effort, which also involves LANL, ORNL, and Babcock and Wilcox Technologies, Inc., will involve new work for the Transient Reactor Test Facility to support NASA experimental-fuel testing. The DOE NTP scope also includes technical project oversight, ground-test trade study development, reactor conceptual design, fuel/fuel element fabrication technology development and testing, high-temperature materials research and development, NTP instrumentation and control development, and project support activities. The current project builds on previous efforts by NASA, DOE, and industry, including the Nuclear Engine for Rocket Vehicle Application engine development program that ended in 1972.

Smithsonian Institution

The Smithsonian Institution continued to contribute to national aerospace goals through a variety of activities in FY 2019. The Smithsonian Astrophysical Observatory (SAO) is a partner of the Harvard-Smithsonian Center for Astrophysics (CfA) in Cambridge, Massachusetts, and represents the largest component of the Smithsonian's space contributors. The organization has more than 300 scientists engaged in a broad program of research in astronomy, astrophysics, Earth and space sciences, and science education. In addition, the Smithsonian National Air and Space Museum (NASM) and the Smithsonian National Museum of Natural History (NMNH) in Washington, DC, contributed to reaching national aerospace goals through their research and education activities.

Three widely reported news stories featured Smithsonian astronomers and space historians in FY 2019. Featured in an "above-the-fold" front-page *New York Times* article and in newspapers around the world were the results of the first-ever imaging of a black hole. This monumental achievement was undertaken by the international Event Horizon Telescope consortium led by SAO astronomer Shep Doeleman. The consortium uses a global array of radio telescopes involving dozens of institutions and hundreds of scientists, including SAO's Submillimeter Array facility on Mauna Kea. The breakthrough discovery is an image of the supermassive black hole in the center of the galaxy Messier 87, located about 55 million light-years away. This black hole contains 6.5 billion times the mass of our Sun. Six initial journal papers were published announcing aspects of this groundbreaking result. "This fulfills our dream to take the first picture of a black hole," said Dr. Doeleman, "We now have access to a cosmic laboratory of extreme gravity where we can test Einstein's Theory of General Relativity and challenge our fundamental assumptions about space and time."



This radio-wavelength image of a black hole is a dramatic first. The radiation arises from hot gas swirling around the object and is distorted into outlining the black hole by the powerful gravitational fields. The object is the supermassive black hole at the nucleus of the galaxy Messier 87. (Credit: The Event Horizon Telescope consortium).

The National Air and Space Museum led the Nation's commemoration of the Apollo 50th anniversary, crowning the week on the National Mall with a full-scale Saturn V rocket projected on the Washington Monument, along with a 17-minute full-motion projection depicting the launch of Apollo 11 and the story of the mission.

The Very Energetic Radiation Imaging Telescope Array System (VERITAS) was used for the first time to measure the diameter of two stars by precise timing of the occultation of the stars by asteroids. The large mirror diameters of VERITAS (12 meters) enabled them to obtain about ten times more precision in the direct measurement

Imaging Saturn V on the Washington Monument. (Photo credit: Jim Preston/Smithsonian National Air and Space Museum)

View of SAO's Fred L. Whipple Observatory basecamp in Arizona and the VERITAS telescope array.

than previously possible with conventional optical telescopes. The project was led by SAO astronomer and VERITAS Director Dr. Winston Benbow.

The Smithsonian plays an ongoing leadership role in space research. NASA's Chandra X-ray Observatory is operated by SAO for NASA, and this year SAO opened Chandra's new Operations Control Center in Cambridge, Massachusetts. Chandra orbits Earth in a three-day elliptical orbit extending about a third of the way to the Moon, and it has exquisite spatial resolution unmatched by any other x-ray telescope, either currently in operation or planned for the future. Chandra operates with high (~70 percent) efficiency, observing critical targets proposed by scientists around the world. Chandra's results appear in an average of 480 highly cited refereed papers per year. Chandra celebrated 20 years of operation in FY 2019, having been launched on July 23, 1999, aboard the Space Shuttle Columbia. It continues to play a pivotal role in studying celestial targets as diverse as comets, black holes, galaxy clusters, supernova remnants, supernovae, dark matter, and dark energy. Recent Chandra discoveries include x-ray emissions from relativistic jets emitted by supermassive black holes in the nuclei of galaxies, complex structures in the hot gas in clusters of galaxies, cosmic-ray acceleration in supernova remnants, and an off-axis jet in a pair of merging neutron stars discovered via gravitational waves.

NASA's Spitzer Space Telescope, now in its 16th year of operation, has continued to produce exciting new views of the universe at infrared wavelengths. Spitzer is the fourth and final space telescope in NASA's Great Observatory series. Spitzer's infrared array camera (IRAC) was developed at SAO with Giovanni Fazio as Principal Investigator, and it was constructed at NASA's Goddard Space

Flight Center. IRAC has been the only instrument operating since Spitzer ran out of cryogens nearly 11 years ago. In 2019, IRAC breakthroughs included studying the atmospheres of several exoplanets (stars around *other* stars) flaring from the supermassive black hole at the center of the Milky Way Galaxy, as well as making measurements on the first known interstellar asteroid, 'Oumuamua, showing that it was not a comet.

The Solar Dynamics Observatory spacecraft provides better-than-high-definition-quality images of the Sun's surface and outer atmosphere, measuring physical conditions that help scientists model the stellar wind and its influence on the "space weather" around Earth. SAO is a major partner in one of its instruments, the Atmospheric Imaging Assembly (AIA), a group of four telescopes that photograph the Sun in ten different wavelength bands once every 12 seconds, producing the most spectacular images ever recorded of the active surface of the Sun. NASA's Interface Region Imaging Spectrograph (IRIS) satellite offers a unique view of the Sun's mysterious chromosphere and transition regions. SAO built the telescope feed and has an active role in IRIS operations, calibration, and science. IRIS is providing information on particle acceleration in hot coronal loops, providing a better understanding of the physical processes powering solar flares. During 2019, SAO scientists also continued their involvement in other solar satellites, including Hinode and the Deep Space Climate Observer.

FY 2019 marked continued progress for the Giant Magellan Telescope (GMT), on which SAO is a team leader. The GMT is a facility for optical and infrared observations that will combine seven huge mirrors to create the world's largest telescope. It will address key questions in cosmology, astrophysics, and the study of planets outside our solar system. NASA's space-based James Webb Space Telescope and the GMT will provide access to complementary biomarkers from exoplanet atmospheres. Four of the seven eight-meter-diameter mirror segments have been fabricated, and two of them have been polished and prepared for shipment to the site in Chile, where this year the excavation of the pier and foundations was completed.

The Tropospheric Emissions: Monitoring Pollution (TEMPO) mission has made excellent progress in 2019. TEMPO successfully completed its development by Ball Aerospace and Technologies Corp. and secured a launch with Maxar Technologies

scheduled for 2022. The mission will study the constituents of the atmosphere in more detail and precision than ever before, compiling a new dataset of atmospheric chemistry as measured from space. TEMPO will be the first space-based instrument to monitor major air pollutants every daylight hour across the North American continent at high spatial resolution.

SAO is a team member of a successful 2019 NASA Medium-Class Explorer (MIDEX) selection, Spectro-Photometer for the History of the Universe, Epoch of Reionization and Ices Explorer (SPHEREx), a space-based telescope that will conduct four all-sky infrared spectral surveys of the sky. SAO manages the Science Center for NASA's Transiting Exoplanet Survey Satellite (TESS), which is engaged in a two-year mission to discover transiting exoplanets with an all-sky survey. Optical follow-up observations of exoplanet candidates found with TESS rely on SAO's facilities in Arizona and Chile to confirm an exoplanet classification.

SAO pursued a wide variety of nationwide STEM education and outreach initiatives, many of which were aimed at broadening public participation in and maximizing the societal benefits of the astrophysics research efforts of the institution. The MicroObservatory is a robotic network of telescopes operated by the CfA for research and public outreach purposes. In 2019, more than 50,000 U.S. students, teachers, members of the public, and amateur astronomers used the MicroObservatory facilities to investigate the Moon, solar system objects, stars, nebulae, galaxies, exoplanets, and other astronomical phenomena. Over the year, SAO continued its popular monthly Observatory Night lectures and observing sessions. Begun by observatory director Harlow Shapley in 1930, these public nights offer the local community an opportunity to learn about the latest advances in astronomy and to view the Moon, stars, and planets through a variety of telescopes. Observatory Night talks also reach worldwide audiences via YouTube.

In FY 2019, the National Air and Space Museum led the Nation's commemoration of the Apollo 11 50th anniversary with a series of programs and events honoring the achievement of Apollo 11 and bringing this story to new generations. First up was "The Spirit of Apollo," an evening at the National Cathedral where speakers, including NASA Administrator Jim Bridenstine and Apollo astronaut Jim Lovell, reflected on the legacy of Apollo 8 and its stunning Earthrise photo that dramatically changed our view of Earth.

In the months leading up to the anniversary, programs across the country included the "Destination Moon" and "New Moon Rising" traveling exhibits, a virtual race challenging runners to combine their miles to equal the mileage to the Moon, and "Apollo in the Parks," in which the museum placed accurately detailed statues of Neil Armstrong's spacesuit in 15 Major League ballparks.

During the anniversary week, the museum ran numerous educational and engaging commemorative programs. The newly restored spacesuit that Neil Armstrong wore on the Moon was displayed in a state-of-the-art climate-controlled case. This exhibit is the culmination of a conservation effort in which NASM has set the standard for the treatment and display of spacesuits. NASM also presented an educational family program, "Discover the Moon Day," in which visitors could interact one-on-one with museum scientists and educators to learn about Apollo and lunar science. The museum stayed open late on the evening of July 20, welcoming over 30,000 visitors to a variety of activities in its "The Eagle Has Landed" public program.

On December 15, 2018, the museum marked a different anniversary—15 years of operation at NASM's Steven F. Udvar-Hazy Center. Approximately 20 million visitors have walked through the doors to see iconic aircraft and spacecraft such as an SR-71, a Concorde, and the Space Shuttle Discovery. In June, the Udvar-Hazy Center also hosted the museum's commemoration of the 75th anniversary of D-Day with a daylong program of hands-on activities and talks by aeronautical experts.

The museum added the last operational EA-6B Prowler to the aircraft collection this year. The Prowler is a highly significant aircraft in the history of electronic warfare. The Aeronautics Department also acquired several works of renowned artist Chesley Bonestell. Opening in February in Orlando, "The Art of the Airport Tower" traveling photography exhibit was curated by Carolyn Russo, who also received a 2019 Archives Research Residency award from the Robert Rauschenberg Foundation. In other Aeronautics research, a study was done on aluminum alloy in the construction of 20th-century aircraft.

The museum's Space History Department published five books, making highly acknowledged contributions to the field, for both scholarly and public audiences. *Spaceflight in the Shuttle Era and Beyond*, by Valerie Neal, received the 2019 Gardner-Lasser Aerospace History Literature Award from the AIAA. *Apollo to the*

Moon: A History in Fifty Objects, by Teasel Muir-Harmony, received broad attention worldwide. Two books were published in the Massachusetts Institute of Technology (MIT) Press Essential Knowledge Series: *GPS*, by Paul Ceruzzi, and *Spaceflight: A Concise History*, by Michael Neufeld. Historian Martin Collins oversaw the production of another scholarly volume as managing editor of the Artefacts Studies in the History of Science and Technology: *Behind the Exhibit: Displaying Science and Technology at World's Fairs and Museums in the Twentieth Century*.

Scientists in the museum's Center for Earth and Planetary Studies (CEPS) participated on the science teams of numerous spacecraft missions and played significant roles in mission operations and planning. They have served this year in such positions as the Mars Exploration Rover (MER) Science Operations Working Group Chair and Cochair of the Mars 2020 Landing Site Steering Committee, leading the process for the crucial landing site selection in Jezero Crater. CEPS staff also served on the InSight Instrument Site Selection Working Group, which is charged with finding locations to deploy instruments. NASM scientists are on the science teams for Mars Express, the Mars Reconnaissance Orbiter (MRO), InSight, the Jupiter Icy Moons Explorer (JUICE), the Lunar Reconnaissance Orbiter (LRO), Dawn, the Europa Clipper, and the proposed Trident Triton flyby mission. In addition, the museum's Director contributed to the development of the Dragonfly mission to Titan that was selected this year for NASA's New Frontiers Program. In this innovative new mission, a drone-like rotorcraft will explore multiple sites on Titan's surface.

This year's science research highlights include groundbreaking research in lunar tectonics. A new look at Apollo seismic data increased our understanding of the shrinking Moon and demonstrated that the Moon is still seismically active today. For Venus, CEPS led the study in which 29 years of Earth-based radar observations determined a mean rotation rate for the planet, which is vital for planning any future landing missions. In Martian fluvial studies, evidence was shown that intense runoff occurred in river channels on Mars much later than previously thought, during a time when the climate was thought to be too cold and dry for such water-related activity.

Other research topics on Mars included the timing of water-related activity in Gale crater and implications for Mars habitability; the degradation history of the

InSight and rover landing sites over time; the global history of water activity on Mars and its role in shaping the landscape through time; lava flows in comparison with other terrestrial planets; subsurface layering of the polar caps; and aeolian studies with implications for understanding the geologic and climatic history of the planet, as well as for mission operations and future mission planning.

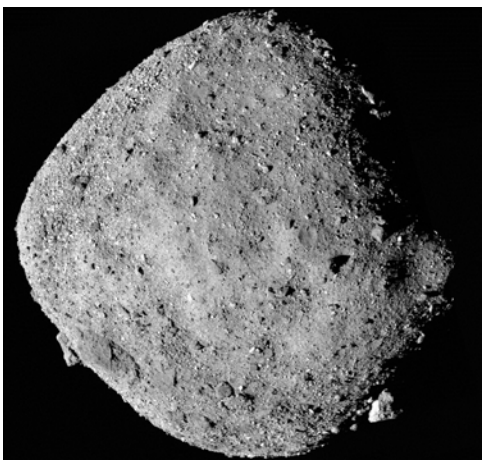
Through our Education Directorate programming, NASM continued to inform and inspire millions nationwide. *STEM in 30*, the museum's Emmy-nominated television show for middle school students, produced nine full episodes covering topics from World War I to Apollo 11 to hurricanes. These videos garnered over 200,000 views and were used by over 100 local cable access networks. Additional video content produced by the museum's education team included hands-on demos with experts (astronauts, engineers, etc.) and segments designed to expose students to diverse people and careers. These videos had over 2.6 million views in FY 2019.

The Teacher Innovator Institute is an intensive STEM professional development program for middle school educators across the United States. Sixty teachers spent two summers expanding their practice to include informal STEM education techniques and learn about authentic learning and integrating real-world problems into their teaching. The Soaring Higher Explorers (S.H.E.) Can STEM summer camp helped 58 middle school students in underrepresented populations and underresourced schools the Washington, DC, area build confidence and competence in STEM subjects. Some of the fundamental elements of the camp included daily STEM-focused design challenges, field trips to meet aerospace professionals, flight training on simulators, and discovery flights with an instructor. In addition, the museum completed its third year of Holt Scholars programming. The focus has narrowed to better meet the needs of sixth-grade students and teachers, but the mission remains the same: to ignite learning and imagination around STEM subjects through the power of our awe-inspiring collection and unique museum experience.

NASM's Explainers Program provides meaningful interactions around STEM topics for visitors of all ages. Staffed by 105 high school and college students over two locations, Explainers facilitated approximately 300,000 interactions with visitors, connecting them to the museum's scientific and historical content. Explainers also extend the reach of the museum via NASM's interactive videoconferencing program with partner schools, engaging over 3,000 middle schoolers who were not

able to visit in person. Explainers deployed a wide variety of programs, activities, and engagement strategies to make the science and history of flight, astronomy, and space exploration accessible to all.

The Smithsonian National Museum of Natural History continued, through the Department of Mineral Sciences and the Offices of Education and Exhibits, its mission of education, research, and curation related to space exploration. Approximately one million people per year visit the Moon, Meteorites and Solar System Gallery of the Geology, Gems and Meteorites Hall, where they can see one of the finest displays of meteorites anywhere in the world, ranging from presolar diamonds separated from the Allende meteorite; to the carbonate-bearing Allan Hills 84001 meteorite, which spurred the debate about past microbial life on Mars; to impactites, including a square-meter section of the Cretaceous-Tertiary (K–T) boundary.



The asteroid Bennu as imaged by the OSIRIS-REx spacecraft.

The collections of the Division of Meteorites continue to grow. Notably, the Smithsonian's partnership with the NSF and NASA in the U.S. Antarctic Meteorite Program surpassed 27,000 individual meteorites collected in Antarctica, including samples from Mars, the Moon, and numerous poorly known asteroids. Provided free of charge to qualified scientists, these samples have addressed fundamental questions about the origin and evolution of our solar system.

Scientists in the Department of Mineral Sciences remain engaged in the study of meteorites and asteroids to unravel their origin in the early solar nebula, their evolution, the differentiation of asteroids in the early history of the solar system, and the geologic evolution of Mars. Glenn MacPherson continues his work on understanding processes in the solar nebula and linking observations made in the laboratory with those made from astronomical observations. Catherine Corrigan continued her studies of fragments of meteorites formed during melting caused

by collisions. Age-dating these samples is key to understanding the extent and duration of the intense impact history of the early solar system. NMNH scientists remained actively engaged in spacecraft missions, with Tim McCoy serving as Co-Investigator on the OSIRIS-REx and Psyche missions. OSIRIS-REx has arrived at asteroid Bennu, having completed the global imaging campaign and beginning intense local imaging for site selection for sample return. In 2020, the spacecraft will sample the surface; in 2023, it will return samples to Earth for study. McCoy, in collaboration with postdoctoral fellow Erica Jawin, is leading efforts to map the geology of the asteroid and will study the mineralogy and origin of the samples when they return to Earth in 2023. He will lead efforts to exhibit a sample of Bennu at NMNH. The Psyche mission, which was selected as one of the newest Discovery missions and is now in the spacecraft construction phase, will visit the asteroid of the same name, which is a 200-kilometer-diameter asteroid thought to be composed of metallic iron, similar to Earth's metallic core. McCoy will lead efforts to study the role of oxidation and reduction in the formation of this asteroid. Public outreach beyond the exhibit continues to be a focus of our efforts, with numerous "Scientist Is In" presentations in the Q?rius learning center at NMNH and outreach efforts beyond the National Mall, including digital outreach through our website.

Appendices

Appendix A-1
U.S. Government Spacecraft Record

(Includes spacecraft from cooperating countries launched by U.S. launch vehicles.)

Calendar Year	Earth Orbit[a]		Earth Escape[b]	
	Success	Failure	Success	Failure
1957	0	1	0	0
1958	5	8	0	4
1959	9	9	1	2
1960	16	12	1	2
1961	35	12	0	2
1962	55	12	4	1
1963	62	11	0	0
1964	69	8	4	0
1965	93	7	4	1
1966	94	12	7	1[b]
1967	78	4	10	0
1968	61	15	3	0
1969	58	1	8	1
1970	36	1	3	0
1971	45	2	8	1
1972	33	2	8	0
1973	23	2	3	0
1974	27	2	1	0
1975	30	4	4	0
1976	33	0	1	0
1977	27	2	2	0
1978	34	2	7	0
1979	18	0	0	0
1980	16	4	0	0
1981	20	1	0	0
1982	21	0	0	0
1983	31	0	0	0
1984	35	3	0	0
1985	37	1	0	0
1986	11	4	0	0
1987	9	1	0	0
1988	16	1	0	0
1989	24	0	2	0
1990	40	0	1	0
1991	32[c]	0	0	0
1992	26[c]	0	1	0
1993	28[c]	1	1	0
1994	31[c]	1	1	0
1995	24[c, d]	2	1	0
1996	30	1	3	0
1997	22[e]	0	1	0
1998	23	0	2	0
1999	35	4	2	0
2000	31[f]	0	0	0
2001	23	0	3	0
2002	18	0	0	1[b]
2003	28[c, f]	0	2	0
2004	8[c]	0	1	0
2005	10	0	2	0
2006	20[d]	0	2	0
2007	16	2	2	0
2008	22[f]	0	0	0
2009	24[f]	1	0	0
2010	15	0	0	0
2011	16	1	3	0
2012	13	0	0	0
2013	18	0	1	0
2014	22	1	0	0
2015	12	1	1	0
2016	27	3	2	0
2017	20	1	0	0
2018	33	0	3	0
2019[g]	26	1	0	0
TOTAL	**1,854**	**164**	**116**	**16**

a. The criterion of success or failure used is attainment of Earth orbit or Earth escape rather than judgment of mission success. "Escape" flights include all that were intended to go to at least an altitude equal to lunar distance from Earth.

b. This Earth-escape failure did attain Earth orbit and, therefore, is included in the Earth-orbit success totals.

c. This excludes commercial satellites. It counts separately spacecraft launched by the same launch vehicle.

d. This counts various sets of microsatellites as a single payload.

e. This includes the Small Spacecraft Technology Initiative (SSTI) Lewis spacecraft that began spinning out of control shortly after it achieved Earth orbit.

f. This includes American spacecraft not launched in the United States.

g. Through September 30, 2019.

Appendix A-2

World Record of Space Launches Successful in Attaining Earth Orbit or Beyond

(Enumerates launches rather than spacecraft; some launches orbited multiple spacecraft.)[a]

Calendar Year	United States[b]	USSR/ CIS	France[c]	Italy[c]	Japan	People's Republic of China	Australia	United Kingdom[c]	European Space Agency	India	Israel	Iran	North Korea	South Korea	New Zealand
1957		2													
1958	5	1													
1959	10	3													
1960	16	3													
1961	29	6													
1962	52	20													
1963	38	17													
1964	57	30													
1965	63	48	1												
1966	73	44	1												
1967	57	66	2	1			1								
1968	45	74													
1969	40	70													
1970	28	81	2	1	1	1									
1971	30	83	1	2	2	1		1							
1972	30	74		1	1										
1973	23	86													
1974	22	81		2	1										
1975	27	89	3	1	2	3									
1976	26	99			1	2									
1977	24	98			2										
1978	32	88			3	1									
1979	16	87			2				1						
1980	13	89			2					1					
1981	18	98			3	1			2	1					
1982	18	101			1	1									
1983	22	98			3	1			2	1					
1984	22	97			3	3			4						
1985	17	98			2	1			3						
1986	6	91			2	2			2						
1987	8	95			3	2			2						
1988	12	90			2	4			7						
1989	17	74			2				7		1				
1990	27	75			3	5			5		1				
1991	20	62			2	1			9	1					
1992	31	55			2	3			7	2					
1993	24	45			1	1			7						
1994	26	49			2	5			6	2					
1995	27	33			1	2			12		1				

Appendix A-2 (cont.)

World Record of Space Launches Successful in Attaining Earth Orbit or Beyond

(Enumerates launches rather than spacecraft; some launches orbited multiple spacecraft.)[a]

Calendar Year	United States[b]	USSR/ CIS	France[c]	Italy[c]	Japan	People's Republic of China	Australia	United Kingdom[c]	European Space Agency	India	Israel	Iran	North Korea	South Korea	New Zealand
1996	32	25			1	3			10	1					
1997	37	28			2	6			12	1					
1998	34	24			2	6			11						
1999	32	26				4			10	1					
2000	30	34				5			12						
2001	23	23			1	1			8	2					
2002	18	23			3	4			11	1	1				
2003	26	21			2	6			4	2					
2004	19	22				8			3	1					
2005	16	26			2	5			5	1					
2006	15	16			5	3			5						
2007	25	33			3	13			8	3	1				
2008[d]	19	26			1	11			7	3					
2009	25	29			3	4			9	4		1			
2010	15	30			2	15			6	1	1				
2011	17	33			3	18			7	3		1			
2012	13	27			2	19			10	2		1	1		
2013[e]	19	29			3	14			7	3				1	
2014[e]	22	31			4	16			10	4	1				
2015	13	16			3	9			8	4		1			
2016	29	25			5	32			14	8	1		1		
2017	20	13			4	8			9	5					
2018	36	12			7	34			8	4					1
2019[f]	26	19			3	30			11	7					1
TOTAL	**1,612**	**3,091**	**10**	**8**	**110**	**314**	**1**	**1**	**281**	**69**	**8**	**4**	**2**	**1**	**2**

a. This includes commercial expendable launches and launches of the Space Shuttle as well as launches to useless orbit.
b. Launches from U.S.-Russia joint platform are included in U.S. totals.
c. Since 1979, all launches for ESA member countries have been joint and are listed under ESA.
d. Since 2008, the ESA statistics include the Soyuz launches from Guiana Space Centre.
e. The data published in the FY 2014 report reflect incorrect totals and have been adjusted.
f. Through September 30, 2019.

Appendix B
SUCCESSFUL LAUNCHES TO ORBIT ON U.S. VEHICLES

October 1, 2018–September 30, 2019

Launch Date Spacecraft Name COSPAR* Designation Launch Vehicle	Mission Objectives	Apogee and Perigee (km), Period (min), Inclination to Equator (°)	Remarks
October 8, 2018 SAOCOM-1A 2018-076A Falcon 9 v1.2	Radar Imaging	633 626 97.2 98	Radar imaging satellite. Can measure moisture in soil to 2 meters.
October 17, 2018 AEHF-4 (Advanced Extremely High Frequency satellite-4, USA 288) 2018-079A Atlas 5-551	Communications	35,790 35,781 1,435.10 0.05	
November 15, 2018 Es'hail 2 2018-090A Falcon 9v1.2	Communications	35,798 35,788 1,436.10 0.1	Communications satellite carrying special non-specified military package; equipped with "sophisticated anti-jamming capabilities."
November 17, 2018 Cygnus NG-10 2018-092A Antares 230	International Space Station	ISS	
December 3, 2018 Spaceflight SSO-A 2018-099A-Y Falcon 9v1.2	Communications/ Earth Observation/ Technology Development	590 573 97.7 96.246	
December 5, 2018 CRS-16 2018-101A Falcon 9 v1.2	International Space Station	ISS	
December 23, 2018 Navstar GPS III-1 (Navstar SVN 74, PRN 04, USA 289) 2018-109A Falcon 9v1.2		20,189 20,171 717.88 54.9	First of third generation.
January 11, 2019 Iridium NEXT 8 2019-002A-K Falcon 9v1.2	Communications	626 609.7 97 86.7	
January 19, 2019 NROL-71 2019-004 Delta 4H	Surveillance/Military	N/A	N/A U.S. National Reconnaissance Office
February 22, 2019 Nusantara Satu+usats 2019-009A, D Falcon 9v1.2	Communications/ Technology Development	35,931 35,915 1,442.85 0.25	Space situational awareness. Part of a project called Small Satellite System for Space Surveillance. Piggybacked all the way to GEO on a communications satellite. First Indonesian High Throughput Satellite, to provide broadband services across the vast archipelago of Indonesia.
March 2, 2019 DM-1/Crew Dragon 2019-011A Falcon 9v1.2	Demo of crew vehicle	ISS	Demo of crew vehicle

* U.N. Committee on Space Research

Appendix B (cont.)

Successful Launches to Orbit on U.S. Vehicles

October 1, 2018–September 30, 2019

Launch Date Spacecraft Name COSPAR* Designation Launch Vehicle	Mission Objectives	Apogee and Perigee (km), Period (min), Inclination to Equator (°)	Remarks
March 15, 2019 NROL 71 2019-014A Delta 4H	Communications	35,795 35,765 1,436.10 0	
April 11, 2019 Arabsat 6A 2019-021A Falcon Heavy	Communications	35,811 35,774 1,436.00 0.01	
April 17, 2019 NG-11 Cygnus 2019-022A Antares 230	International Space Station	ISS	
May 4, 2019 CRS-17 2019-025A Falcon 9v1.2	International Space Station	ISS	
May 24, 2019 Starlink 0.9 (60 sat) 2019-029A-Z Falcon 9v1.2	Communications	541 536 95.7 53	
June 12, 2019 Radar Constellation Mission (RCM) 2019-033A-C Falcon 9v1.2	Communications	603 584 96.6 97.7	Three-satellite constellation, $900 million mission surveying the Arctic, maritime waters, forests, and farmland for the Canadian government.
June 25, 2019 STP-2 2019-036A-AB Falcon Heavy	Earth Observation/ Technology Development	1,321 767 108.014 27.01	Collect atmospheric data for weather prediction and for ionosphere, climate, and gravity research.
July 25, 2019 CRS-18 2019-044A Falcon 9 v1.2	International Space Station	ISS	
August 6, 2019 AMOS-17 2019-050A Falcon 9 v1.2	Communications	35,793 35,777 1,436.04 0	Replaces Amos 5, which failed in 2015.
August 8, 2019 AEHF-5 (Advanced Extremely High Frequency satellite-5) 2019-051A-B Atlas 5-551	Technology Development	35,224 216 620.20 25.9	Testing orbital debris tracking capabilities.
August 22, 2019 Navstar GPS III-2 2019-056A Delta 4M+4.2	Navigation/Global Positioning	20,203 20,188 718.01 55.1	

Appendix C
HUMAN SPACEFLIGHTS

October 1, 2018–September 30, 2019

Spacecraft	Launch Date	Crew	Flight Time (d:h:min)	Highlights
Soyuz MS-10 Expedition 57	October 11, 2018	Alexey Ovchinin Nick Hague	19:41	Aborted shortly after launch.
Soyuz MS-11 Expedition 58	December 3, 2018	Oleg Kononenko Anne McClain David Saint-Jacques	203:15:15	Robotic Refueling Mission-3 Study on Wound Healing CASIS Protein Crystal Growth-16
Soyuz MS-12 Expedition 59	March 14, 2019	Nick Hague Christina Koch Alexey Ovchinin	202:15:46	Study on Effectiveness of Potential Pharmaceuticals in Humans Astrobee Hermes Facility Orbiting Carbon Observatory 3
Soyuz MS-13 Expedition 60	July 20, 2019	Andrew Morgan Luca Parmitano Alexander Skvortsov	200:16:44	BioFabrication Facility Inertial Spreading Biorock Goodyear Tire
Soyuz MS-15 Expedition 61	September 25, 2019	Jessica Meir Oleg Skripochka Hazzaa Ali Almansoori	171:11:11	AMS-02 AstroRad Vest ANALOG-1 Targeting Improved Cotton Through Orbital Cultivation AzTechSat-1

Appendix D-1A

SPACE ACTIVITIES OF THE U.S. GOVERNMENT

HISTORICAL TABLE OF BUDGET AUTHORITY

(in millions of real-year dollars)

FY	NASA Total	NASA Space	DOD[a]	Other[b]	DOE[c]	DOC	DOI	USDA	NSF[d]	DOT	Total Space
1959	331	261	490	34	34						785
1960	524	462	561	43	43						1,066
1961	964	926	814	68	68						1,808
1962	1,825	1,797	1,298	199	148	51					3,294
1963	3,673	3,626	1,550	257	214	43					5,433
1964	5,100	5,016	1,599	213	210	3					6,828
1965	5,250	5,138	1,574	241	229	12					6,953
1966	5,175	5,065	1,689	214	187	27					6,968
1967	4,966	4,830	1,664	213	184	29					6,707
1968	4,587	4,430	1,922	174	145	28	0.2	1			6,526
1969	3,991	3,822	2,013	170	118	20	0.2	1	31		6,005
1970	3,746	3,547	1,678	141	103	8	1	1	28		5,366
1971	3,311	3,101	1,512	162	95	27	2	1	37		4,775
1972	3,307	3,071	1,407	133	55	31	6	2	39		4,611
1973	3,406	3,093	1,623	147	54	40	10	2	41		4,863
1974	3,037	2,759	1,766	158	42	60	9	3	44		4,683
1975	3,229	2,915	1,892	158	30	64	8	2	54		4,965
1976	3,550	3,225	1,983	168	23	72	10	4	59		5,376
TQ*	932	849	460	43	5	22	3	1	12		1,352
1977	3,818	3,440	2,412	194	22	91	10	6	65		6,046
1978	4,060	3,623	2,738	226	34	103	10	8	71		6,587
1979	4,596	4,030	3,036	248	59	98	10	8	73		7,314
1980	5,240	4,680	3,848	231	40	93	12	14	72		8,759
1981	5,518	4,992	4,828	234	41	87	12	16	78		10,054
1982	6,044	5,528	6,679	313	61	145	12	15	80		12,520
1983	6,875	6,328	9,019	327	39	178	5	20	85		15,674
1984	7,458	6,858	10,195	395	34	236	3	19	103		17,448
1985	7,573	6,925	12,768	584	34	423	2	15	110		20,277
1986	7,807	7,165	14,126	477	35	309	2	23	108		21,768
1987	10,923	9,809	16,287	466	48	278	8	19	112	1	26,562
1988	9,062	8,322	17,679	741	241	352	14	18	115	1	26,742
1989	10,969	10,097	17,906	560	97	301	17	21	121	3	28,563
1990	12,324	11,460	15,616	506	79	243	31	25	124	4	27,582
1991	14,016	13,046	14,181	772	251	251	29	26	211	4	27,999

a. DOD reported that improvements to the estimating methodology resulted in a change in estimated budget authority and outlays starting in FY 2013.

b. The Other column is the total of the non-NASA and non-DOD budget authority figures that appear in the succeeding columns. The total is sometimes different from the sum of the individual figures because of rounding. The Total Space column does not include the NASA Total column because the latter includes budget authority for aeronautics as well as space. For the years 1989–97, this Other column also includes small figures for the Environmental Protection Agency (EPA), as well as $2.1 billion for the replacement of Space Shuttle Challenger in 1987.

c. DOE has recalculated its space expenditures since 1998.

d. The NSF has recalculated its space expenditures since 1980, making them significantly higher than reported in previous years.

* Transition Quarter

Appendix D-1A (cont.)

SPACE ACTIVITIES OF THE U.S. GOVERNMENT

HISTORICAL TABLE OF BUDGET AUTHORITY

(in millions of real-year dollars)

FY	NASA Total	NASA Space	DOD[a]	Other[b]	DOE[c]	DOC	DOI	USDA	NSF[d]	DOT	Total Space
1992	14,317	13,199	15,023	798	223	327	34	29	181	4	29,020
1993	14,310	13,064	14,106	731	165	324	33	25	180	4	27,901
1994	14,570	13,022	13,166	632	74	312	31	31	179	5	26,820
1995	13,854	12,543	10,644	759	60	352	31	32	278	6	23,946
1996	13,884	12,569	11,514	828	46	472	36	37	231	6	24,911
1997	13,709	12,457	11,727	789	35	448	42	39	219	6	24,973
1998	13,648	12,321	12,359	839	103	435	43	39	213	6	25,519
1999	13,653	12,459	13,203	982	105	575	59	37	200	6	26,644
2000	13,601	12,521	12,941	1,056	164	575	60	44	207	6	26,518
2001	14,230	13,304	14,326	1,062	145	577	60	36	232	12	28,692
2002	14,868	13,871	15,740	1,180	166	644	64	28	266	12	30,791
2003	15,364	14,360	19,388	1,305	191	649	74	42	337	12	35,053
2004	15,379	14,322	19,115	1,464	209	745	71	61	366	12	34,901
2005	16,198	15,234	19,690	1,551	229	807	70	73	360	12	36,475
2006	16,623	15,765	22,114	1,647	245	860	82	84	364	12	39,526
2007	16,285	15,568	22,418	1,680	200	912	87	65	404	12	39,666
2008	17,117	16,502	24,795	1,698	195	862	90	59	479	13	42,995
2009	17,775	17,275	26,528	1,868	200	1,078	64	27	485	14	45,671
2010	18,725	18,228	26,463	2,057	203	1,261	67	27	484	15	46,748
2011	18,432	17,898	27,234	2,186	229	1,444	66	20	412	15	47,318
2012	17,773	17,203	26,677	2,580	199	1,876	76	7	406	16	46,460
2013	17,395	16,865	10,818	2,578	185	1,865	84	20	409	15	30,261
2014	17,647	17,081	10,400	2,839	174	2,087	82	19	461	16	30,320
2015	18,010	17,359	10,325	3,010	182	2,223	83	19	485	18	30,694
2016	19,285	18,645	6,967	3,159	178	2,346	87	19	508	22	28,771
2017	19,653	18,993	10,316	2,995	172	2,214	85	20	480	24	32,305
2018	20,736	19,976	7,861	2,953	175	2,099	79	16	556	29	30,790
2019	21,500	20,775	9,970	12,305	217	1,667	84	19	581	36	43,050

Appendix D-1B

SPACE ACTIVITIES OF THE U.S. GOVERNMENT

HISTORICAL TABLE OF BUDGET AUTHORITY

(in millions of inflation-adjusted FY 2019 dollars)

FY	Inflation Factors	NASA Total	NASA Space	DOD[a]	Other[b]	DOE[c]	DOC	DOI	USDA	NSF[d]	DOT	Total Space
1959	6.866	2,273	1,792	3,364	233	233						5,390
1960	6.771	3,548	3,128	3,798	291	291						7,217
1961	6.682	6,442	6,188	5,439	454	454						12,081
1962	6.615	12,073	11,888	8,587	1,316	979	337					21,791
1963	6.538	24,015	23,708	10,134	1,680	1,399	281					35,523
1964	6.456	32,925	32,382	10,323	1,375	1,356	19					44,080
1965	6.347	33,319	32,608	9,989	1,530	1,453	76					44,127
1966	6.213	32,154	31,470	10,494	1,330	1,162	168					43,294
1967	6.030	29,945	29,125	10,034	1,284	1,110	175					40,443
1968	5.827	26,728	25,813	11,199	1,015	845	163	1	6			38,028
1969	5.573	22,241	21,299	11,218	950	658	111	1	6	174		33,467
1970	5.290	19,815	18,763	8,876	746	545	42	5	5	148		28,385
1971	5.034	16,668	15,610	7,611	815	478	136	10	5	186		24,037
1972	4.806	15,893	14,759	6,762	641	264	149	29	10	189		22,162
1973	4.605	15,685	14,244	7,474	679	249	184	46	9	190		22,397
1974	4.299	13,056	11,861	7,592	679	181	258	39	13	189		20,132
1975	3.897	12,583	11,359	7,373	615	117	249	31	8	209		19,346
1976	3.643	12,933	11,749	7,224	613	84	262	36	15	216		19,586
TQ*	3.536	3,296	3,002	1,627	152	18	78	11	4	42		4,781
1977	3.398	12,972	11,688	8,195	657	75	309	34	20	219		20,540
1978	3.183	12,924	11,532	8,715	719	108	328	32	25	226		20,967
1979	2.946	13,538	11,870	8,943	730	174	289	29	24	215		21,543
1980	2.709	14,196	12,679	10,425	626	108	252	33	38	195		23,730
1981	2.467	13,612	12,314	11,910	578	101	215	30	39	193		24,802
1982	2.306	13,940	12,750	15,404	721	141	334	28	35	184		28,875
1983	2.210	15,193	13,984	19,931	723	86	393	11	44	188		34,638
1984	2.134	15,912	14,632	21,752	842	73	504	6	41	219		37,226
1985	2.065	15,635	14,298	26,361	1,205	70	873	4	31	226		41,864
1986	2.019	15,765	14,469	28,526	963	71	624	4	46	218		43,958
1987	1.975	21,574	19,373	32,168	920	95	549	16	38	221	2	52,461
1988	1.913	17,338	15,922	33,824	1,418	461	673	27	34	220	2	51,164
1989	1.839	20,170	18,566	32,925	1,030	178	553	31	39	223	6	52,521
1990	1.774	21,861	20,328	27,700	897	140	431	55	44	219	7	48,925
1991	1.713	24,006	22,345	24,289	1,323	430	430	50	45	362	7	47,956

a. DOD reported that improvements to the estimating methodology resulted in a change in estimated budget authority and outlays starting in FY 2013.

b. The Other column is the total of the non-NASA and non-DOD budget authority figures that appear in the succeeding columns. The total is sometimes different from the sum of the individual figures because of rounding. The Total Space column does not include the NASA Total column because the latter includes budget authority for aeronautics as well as space. For the years 1989–97, this Other column also includes small figures for the Environmental Protection Agency (EPA), as well as $2.1 billion for the replacement of Space Shuttle Challenger in 1987.

c. DOE has recalculated its space expenditures since 1998.

d. The NSF has recalculated its space expenditures since 1980, making them significantly higher than reported in previous years.

* Transition Quarter

Appendix D-1B (cont.)

SPACE ACTIVITIES OF THE U.S. GOVERNMENT

HISTORICAL TABLE OF BUDGET AUTHORITY

(in millions of inflation-adjusted FY 2019 dollars)

FY	Inflation Factors	NASA Total	NASA Space	DOD[a]	Other[b]	DOE[c]	DOC	DOI	USDA	NSF[d]	DOT	Total Space
1992	1.671	23,924	22,056	25,104	1,333	373	546	57	48	302	7	48,493
1993	1.633	23,364	21,330	23,031	1,193	269	529	54	41	294	7	45,554
1994	1.598	23,281	20,808	21,038	1,011	118	499	50	50	287	8	42,856
1995	1.565	21,675	19,624	16,653	1,187	94	551	49	50	435	9	37,464
1996	1.536	21,322	19,302	17,682	1,271	71	725	55	57	354	9	38,256
1997	1.509	20,686	18,797	17,695	1,191	53	676	63	59	331	9	37,683
1998	1.490	20,340	18,362	18,419	1,251	154	648	64	58	318	9	38,032
1999	1.471	20,089	18,332	19,427	1,445	154	846	87	54	294	9	39,204
2000	1.442	19,610	18,053	18,658	1,522	236	829	87	63	298	9	38,233
2001	1.409	20,044	18,740	20,179	1,496	204	813	85	51	327	17	40,415
2002	1.386	20,612	19,230	21,821	1,636	230	893	89	39	369	17	42,687
2003	1.362	20,918	19,551	26,397	1,777	260	884	101	57	459	16	47,725
2004	1.330	20,448	19,043	25,416	1,947	278	991	94	81	487	16	46,405
2005	1.290	20,900	19,656	25,405	2,001	295	1,041	90	94	464	15	47,063
2006	1.250	20,783	19,710	27,648	2,059	306	1,075	103	105	455	15	49,417
2007	1.217	19,820	18,948	27,285	2,045	243	1,110	106	79	492	15	48,277
2008	1.192	20,411	19,678	29,567	2,025	233	1,028	107	70	571	16	51,269
2009	1.179	20,954	20,364	31,272	2,202	236	1,271	75	32	572	17	53,838
2010	1.169	21,885	21,305	30,929	2,404	237	1,474	78	31	566	18	54,638
2011	1.146	21,121	20,510	31,208	2,504	262	1,655	76	22	472	17	54,222
2012	1.125	19,988	19,346	30,001	2,901	224	2,110	85	8	457	18	52,249
2013	1.104	19,209	18,624	10,818	2,847	204	2,059	93	22	452	17	33,417
2014	1.083	19,119	17,081	10,400	2,839	174	2,087	82	19	461	16	32,850
2015	1.071	19,290	17,359	10,325	3,010	182	2,223	83	19	485	18	30,694
2016	1.062	20,474	18,645	6,967	3,159	178	2,346	87	19	508	22	28,771
2017	1.043	20,501	18,993	10,316	2,995	172	2,214	85	20	480	24	32,305
2018	1.019	21,138	19,976	7,861	2,953	175	2,099	79	16	556	29	30,790
2019	1.000	21,500	20,775	9,970	12,305	217	1,667	84	19	581	36	43,050

Appendix D-2

Federal Space Activities Budget

(in millions of dollars by fiscal year)

Federal Agencies	Budget Authority 2017 actual	2018 actual	2019 actual	2020 est.	Budget Outlays 2017 actual	2018 actual	2019 actual	2020 est.
NASA[1]	18,993.3	19,976.1	20,775	21,775	18,074	19,792	20,886	21,232
DOD[2, 3]	10,136	7,861	9,970	11,887	10,400	9,296	9,970	11,887
DOE[4, 5]	172	175.39	217	191	173	165.4	193	208
DOC[6]	2,214	2,099.269	1,666.64	1,444.61	1,938	2,068.22	1,666.64	1,444.61
DOI[7]	85.4	78.5	84.3	84.3	85	78.5	84.3	84.3
USDA[8]	20.1	15.96	18.57	20.69	18.4	16.08	20.08	20.69
DOT	24.2	28.959	36.449	64.569	24.2	28.959	36.449	64.569
NSF[9]	480.1	555.59	581.08	429.31	352.7	462.15	444.62	406.33

1. The FY 2020 estimate is based on the prior year's Outlays versus Budget Authority. FY 2020 Enacted Funding Levels were not available at the time this report was requested. The FY 2020 Budget Authority Estimate is based on the 2020 President's Budget Request.
2. Does not include DOD or Office of the Director of National Intelligence (ODNI) intelligence programs. DOD FY 2017, FY 2018, and FY 2019 figures for Budget Authority and Outlays are estimated at the time of preparing this report. Improvements to the estimating methodology resulted in a change in estimated Budget Authority and Outlays starting in FY 2013.
3. At the time of preparing this report, DOD submitted estimates as billions of dollars, so the figures are rounded to the nearest hundred million.
4. In prior years, the High Energy Physics program also reported Ground- and Underground-Based Astrophysics Projects. These projects and the associated funding are no longer included, starting in the FY 2009 report.
5. At the time of preparing this report, DOE submitted estimates, not actuals.
6. The Budget Outlays columns reflect dollars "costed" in a fiscal year specific to that same fiscal year's appropriated dollars.
7. The USGS has recalculated its space and aeronautics expenditures for 2019. For this submission to the Aeronautics and Space Report of the President, the USGS is only reporting on outlays for Satellite Operations (space funding), shown here in Appendix D-2, and the 3D Elevation Program (3DEP) (aeronautics funding), shown in Appendix D-3.
8. At the time of preparing this report, the USDA submitted FY 2019 estimates, not actuals.
9. "Actual" = actual obligations.

Appendix D-3

Federal Aeronautics Activities Budget

(in millions of dollars by fiscal year)

Federal Agencies	Budget Authority 2017 actual	2018 actual	2019 actual	2020 est.	Budget Outlays 2017 actual	2018 actual	2019 actual	2020 est.
NASA[1]	660	760	725	784	629	650	705	703
USDA[2, 3]	38.6	42.21	70.22	76.70	70.7	47.34	63.16	66.56
DOD[4, 5]	53,440	51,466	58,236	57,660	33,213	55,208	58,236	57,660
DOI[6]	35	37.7	37.7		35.1	37.5	37.7	
DOT	3,014.9	3,420.91	3,173.09	3,399.897	2,674.90	2,696.659	2,956.3	3,692.435

1. The FY 2020 estimate is based on the prior year's Outlays versus Budget Authority.
2. At the time of preparing this report, the USDA submitted estimates, not actuals.
3. FY 2017 was the first time the National Resources Conservation Service (NRCS) reported state expenditures for this report. FY 2017 Outlays represent national lidar initiatives, where NRCS spent $3 million and state offices spent another $33 million.
4. DOD FY 2017, FY 2018, and FY 2019 figures for Budget Authority and Outlays are estimated at the time of preparing this report. Improvements to the estimating methodology resulted in a change in estimated Budget Authority and Outlays starting in FY 2013.
5. At the time of preparing this report, DOD submitted estimates as billions of dollars, so the figures are rounded to the nearest hundred million.
6. The USGS has recalculated its space and aeronautics expenditures for 2019. For this submission to the Aeronautics and Space Report of the President, the USGS is only reporting on outlays for Satellite Operations (space funding), shown in Appendix D-2, and the 3D Elevation Program (3DEP) (aeronautics funding), shown here in Appendix D-3.

Appendix E

Space Policy Directive-4 of February 19, 2019

Establishment of the United States Space Force

Section 1. Introduction. Space is integral to our way of life, our national security, and modern warfare. Although United States space systems have historically maintained a technological advantage over those of our potential adversaries, those potential adversaries are now advancing their space capabilities and actively developing ways to deny our use of space in a crisis or conflict. It is imperative that the United States adapt its national security organizations, policies, doctrine, and capabilities to deter aggression and protect our interests. Toward that end, the Department of Defense shall take actions under existing authority to marshal its space resources to deter and counter threats in space, and to develop a legislative proposal to establish a United States Space Force as a sixth branch of the United States Armed Forces within the Department of the Air Force. This is an important step toward a future military department for space. Under this proposal, the United States Space Force would be authorized to organize, train, and equip military space forces of the United States to ensure unfettered access to, and freedom to operate in, space, and to provide vital capabilities to joint and coalition forces in peacetime and across the spectrum of conflict.

Sec. 2. Definitions. For the purposes of this memorandum and the legislative proposal directed by section 3 of this memorandum, the following definitions shall apply:

(a) The term "United States Space Force" refers to a new branch of the United States Armed Forces to be initially placed by statute within the Department of the Air Force.

(b) The term "Department of the Space Force" refers to a future military department within the Department of Defense that will be responsible for organizing, training, and equipping the United States Space Force.

(c) The term "United States Space Command" refers to a Unified Combatant Command to be established pursuant to the Presidential memorandum of December 18, 2018 (Establishment of United States Space Command as a Unified Combatant Command), that will be responsible for Joint Force space operations as will be assigned in the Unified Command Plan.

Sec. 3. Legislative Proposal and Purpose. The Secretary of Defense shall submit a legislative proposal to the President through the Office of Management and Budget that would establish the United States Space Force as a new armed service within the Department of the Air Force.

The legislative proposal would, if enacted, establish the United States Space Force to organize, train, and equip forces to provide for freedom of operation in, from, and to the space domain; to provide independent military options for national leadership; and to enhance the lethality and effectiveness of the Joint Force. The United States Space Force should include both combat and combat support functions to enable prompt and sustained offensive and defensive space operations, and joint operations in all domains. The United States Space Force shall be organized, trained, and equipped to meet the following priorities:

(a) Protecting the Nation's interests in space and the peaceful use of space for all responsible actors, consistent with applicable law, including international law;

(b) Ensuring unfettered use of space for United States national security purposes, the United States economy, and United States persons, partners, and allies;

(c) Deterring aggression and defending the Nation, United States allies, and United States interests from hostile acts in and from space;

(d) Ensuring that needed space capabilities are integrated and available to all United States Combatant Commands;

(e) Projecting military power in, from, and to space in support of our Nation's interests; and

(f) Developing, maintaining, and improving a community of professionals focused on the national security demands of the space domain.

Sec. 4. Scope.

(a) The legislative proposal required by section 3 of this memorandum shall, in addition to the provisions required under section 3 of this memorandum, include provisions that would, if enacted:

(i) consolidate existing forces and authorities for military space activities, as appropriate, in order to minimize duplication of effort and eliminate bureaucratic inefficiencies; and

(ii) not include the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, the National Reconnaissance Office, or other non-military space organizations or missions of the United States Government.

(b) The proposed United States Space Force should:

(i) include, as determined by the Secretary of Defense in consultation with the Secretaries of the military departments, the uniformed and civilian personnel conducting and directly supporting space operations from all Department of Defense Armed Forces;

(ii) assume responsibilities for all major military space acquisition programs; and

(iii) create the appropriate career tracks for military and civilian space personnel across all relevant specialties, including operations, intelligence, engineering, science, acquisition, and cyber.

Sec. 5. United States Space Force Budget. In accordance with the Department of Defense budget process, the Secretary of Defense shall submit to the Director of the Office of Management and Budget a proposed budget for the United States Space Force to be included in the President's Fiscal Year 2020 Budget Request.

Sec. 6. United States Space Force Organization and Leadership.

(a) The legislative proposal required by section 3 of this memorandum shall create a civilian Under Secretary of the Air Force for Space, to be known as the Under Secretary for Space, appointed by the President by and with the advice and consent of the Senate.

(b) The legislative proposal shall establish a Chief of Staff of the Space Force, who will be a senior military officer in the grade of General or Admiral, and who shall serve as a member of the Joint Chiefs of Staff.

Sec. 7. Associated Elements.

(a) A Unified Combatant Command for space, to be known as the United States Space Command, will be established consistent with law, as directed on December 18, 2018. This command will have all of the responsibilities of a Unified Combatant Command in addition to the space-related responsibilities previously assigned to United States Strategic Command. It will also have the responsibilities of the Joint Force provider and Joint Force training for space operations forces. Moving expeditiously toward a Unified Combatant Command reflects the importance of warfighting in space to the Joint Force. The commander of this command will lead space warfighting through global space operations that may occur in the space domain, the terrestrial domains, or through the electromagnetic spectrum.

(b) With forces provided by the United States Space Force and other United States Armed Forces, the United States Space Command shall ensure unfettered access to, and freedom to operate in, space and provide vital effects and capabilities to joint and coalition forces during peacetime and across the spectrum of conflict.

Sec. 8. Relationship with National Intelligence. The Secretary of Defense and the Director of National Intelligence shall create and enhance mechanisms for collaboration between the Department of Defense and the United States Intelligence Community in order to increase unity of effort and the effectiveness of space operations. The Secretary of Defense and the Director of National Intelligence shall provide a report to the President within 180 days of the date of this memorandum on steps they have taken and are planning to take toward these ends, including legislative proposals as necessary and appropriate.

Sec. 9. Operational Authorities. In order to ensure that the United States Space Force and United States Space Command have the necessary operational authorities, the National Space Council and the National Security Council shall coordinate an accelerated review of space operational authorities. Within 90 days of the date of this memorandum, the Secretary of Defense shall present to the National Space Council and the National Security Council proposed relevant authority changes for the President's approval. The National Space Council and the National Security Council shall then conduct an interagency review of the Secretary's proposal and make recommendations to the President on appropriate authorities, to be completed no later than 60 days from the date the Secretary of Defense presents his proposal to the councils.

Sec. 10. Periodic Review. As the United States Space Force matures, and as national security requires, it will become necessary to create a separate military department, to be known as the Department of the Space Force. This department will take over some or all responsibilities for the United States Space Force from the Department of the Air Force. The Secretary of Defense will conduct periodic reviews to determine when to recommend that the President seek legislation to establish such a department.

Sec. 11. General Provisions.

(a) Nothing in this memorandum shall be construed to impair or otherwise affect:

(i) the authority granted by law to an executive department or agency, or the head thereof; or

(ii) the functions of the Director of the Office of Management and Budget relating to budgetary, administrative, or legislative proposals.

(b) This memorandum shall be implemented consistent with applicable law and United States national and homeland security requirements, and subject to the availability of appropriations.

(c) This memorandum is not intended to, and does not, create any right or benefit, substantive or procedural, enforceable at law or in equity by any party against the United States, its departments, agencies, or entities, its officers, employees, or agents, or any other person.

(d) The Secretary of Defense is authorized and directed to publish this memorandum in the Federal Register.

Donald J. Trump

The White House,

February 19, 2019

Acronyms

3DEP	3D Elevation Program

A

AAM	Advanced Air Mobility
ACEP	Agricultural Conservation Easement Program
ACES	Atomic Clock Ensemble in Space
ACN	Aircraft Notebook
ACO	Announcement of Collaboration Opportunity
ADS-B	Automatic Dependent Surveillance–Broadcast
AE	Archive Explorer
AEFS	Advanced Electronic Flight Strips
AEHF	Advanced Extremely High Frequency
AES	Advanced Exploration Systems
AFB	Air Force Base
AFCSCO	Air Force Commercial SATCOM Office
AFSPC	Air Force Space Command
AGBRESA	Artificial Gravity Bed Rest-ESA
AGS	Atmospheric and Geospace Science Division
AHE	Advanced Hawkeye
AIA	Atmospheric Imaging Assembly
AIAA	American Institute of Aeronautics and Astronautics
AIS	Automated Information System
ALE	Air Launched Effects
ALMA	Atacama Large Millimeter/Submillimeter Array
AM	additive manufacturing
AMAPPS	Atlantic Marine Assessment Program for Protected Species
AMEC	Alaska Mapping Executive Committee
AMISR	Advanced Modular Incoherent-Scatter Radar
AMPERE	Active Magnetosphere and Planetary Electrodynamics Response Experiment
AMS	Autonomous Modular Sensor; Alpha Magnetic Spectrometer
ANSI	American National Standards Institute
AO	Arecibo Observatory
AoA	Analysis of Alternatives
AoR	Area of Responsibility
APD	Astrophysics Division
APHIS	Animal and Plant Health Inspection Service
APKWS	Advanced Precision Kill Weapon System
APL	Applied Physics Laboratory
APRSAF	Asia-Pacific Regional Space Agency Forum
ARD	Analysis Ready Data
ARIA	Asia Reassurance Initiative Act
ARM	Atmospheric Radiation Measurement Research Facility
ARMD	Aeronautics Research Mission Directorate
ARS	Agricultural Research Service
ARTCC	Air Route Traffic Control Center
ARTEMIS	Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun
AS	Atmosphere Section
ASB	Agricultural Statistics Board

ASBU	Aviation System Block Upgrade
ASD	agricultural statistics district
ASE	Aviation Survivability Equipment
ASM	artisanal and small-scale mining
ASME	American Society of Mechanical Engineers
ASPRS	American Society for Photogrammetry and Remote Sensing
AST	Office of Commercial Space Transportation; Division of Astronomical Sciences
ASU	Group on the Sector Understanding on Export Credits for Civil Aircraft (the "Aircraft Sector Understanding")
ASuW	Anti-Surface Warfare
ATC	air traffic control
ATCA	Air Traffic Control Association
ATHENA	Advanced Telescope for High-ENergy Astrophysics
ATLAS	Advanced Twin Lifting and Aerobic System
ATM	air traffic management
ATR	Advanced Test Reactor
AWiFS	Advanced Wide Field Sensor

B

BAA	Broad Agency Announcement
BABAR	Broadband Absolute Bolometer Array
BAER	Burned Area Emergency Response
BBD	beech bark disease
BICEP3	Background Imaging of Cosmic Extragalactic Polarization
BICY	Big Cypress National Preserve
BIS	Bureau of Industry and Security
BLAST-TNG	Balloon-borne Large-Aperture Submillimeter Telescope–The Next Generation
BLM	Bureau of Land Management
BNL	Brookhaven National Laboratory
BoD	Board of Directors
BOEM	Bureau of Ocean Energy Management
BOR	Bureau of Reclamation
BPS	Biological and Physical Sciences

C

C&N	communication and navigation
C2	command and control
CAB	Combat Aviation Brigade
CAE	Center for Agribusiness Excellence
CAESR	Carbon Absolute Electrical Substitution Radiometer
CAL	Cold Atom Laboratory
CANVAS	Climatology of Anthropogenic and Natural Very Low Frequency wave Activity in Space
CAPS	Control and Planning Segment
CAPSTONE	Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment
CAS	Commercial Augmentation System
CCAFS	Cape Canaveral Air Force Station
CCC	Commodity Credit Corporation
CCDC	Continuous Change Detection and Classification
CCOR	Compact Coronagraph
CCP	Commercial Crew Program
CCS	Counter Communications System
CCSC	Collaborations for Commercial Space Capabilities
CCSDS	Consultative Committee for Space Data Systems

CDD	Capability Development Document
CDL	Cropland Data Layer
CEDAR	Coupling, Energetics, and Dynamics of Atmospheric Regions
CENTCOM	Central Command
CEPS	Center for Earth and Planetary Studies
CERP	Comprehensive Everglades Restoration Plan
CfA	Harvard-Smithsonian Center for Astrophysics
CFT	Crewed Flight Test; Cross-Functional Team
CHNS	Committee for Homeland and National Security
CHOMPTT	CubeSat Handling of Multisystem Precision Time Transfer
CIR	Color Infrared
CMB	cosmic microwave background
CMWS	Common Missile Warning System
CNES	Centre National d'Études Spatiales
CNT ESR	Carbon Nanotube Electrical Substitution Radiometer
CO	carbon monoxide
COMSATCOM	Commercial SATCOM
CONOPS	Concept of Operations
CONUS	contiguous United States
COPUOS	Committee on the Peaceful Uses of Outer Space
COSMIC	Constellation Observing System for Meteorology, Ionosphere, and Climate
COSMIC-2	Constellation Observing System for Meteorology, Ionosphere, and Climate 2
COSPAS-SARSAT	Search and Rescue Satellite-Aided Tracking
COWVR	Compact Ocean Wind Vector Radiometer
CP	Competitive Prototype
CPT	Command Post Terminals
CREMA	Coastal Resource Evaluation for Management Application
CREWS	Crew Recommender for Effective Work in Space
CRP	constant-rate production
CRS	Commercial Resupply Services
CS	Commercial Service
CSG	Carrier Strike Group
CSIM	Compact Solar Irradiance Monitor
CSLI	CubeSat Launch Initiative
CSM	Crew and Service Module
CSP	Cold Spray Process
CT	computerized tomography
CTIM	Compact Total Irradiance Monitor
CVN	aircraft carrier with nuclear propulsion
CVW	Carrier Air Wing
CY	calendar year

D

DAC	Design Analysis Cycle
DAMIEN	Detecting and Mitigating the Impact of Earth-Bound Near-Earth Objects
DARPA	Defense Advanced Research Projects Agency
DART	Double Asteroid Redirection Test
Data Comm	Data Communications
DBS	direct broadcast satellite
DEM	digital elevation model
DKIST	Daniel K. Inouye Solar Telescope
DLR	German Aerospace Center
DMC	Disaster Monitoring Constellation
DMSP	Defense Meteorological Satellite Program

dNBR	Delta NBR
dNDVI	Delta NDVI
DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
DOI	Department of the Interior
DON	Department of the Navy
DOS	Department of State
DSAC	Deep Space Atomic Clock
DSCOVR	Deep Space Climate Observatory
DSM	Digital Surface Model
DSN	Deep Space Network
DTM	Digital Terrain Model

E

EBL	extragalactic background light
EC	European Commission
ECOSTRESS	ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station
eCRYO	Evolvable Cryogenics Project
EDU	engineering design unit
EELV	Evolved Expendable Launch Vehicle
EGS	Exploration Ground Systems
EHT	Event Horizon Telescope
ELaNa	Educational Launch of NanoSatellites
ELV	expendable launch vehicle
EOC	Early Operational Capability
EOS	Earth Observing System
EPS	Enhanced Polar System
EPS-R	EPS-Recapitalization
ERAM	En Route Automation Modernization
EROS	Earth Resources Observation Systems
ESA	European Space Agency; Endangered Species Act
ESBMC2	Enterprise Space Battle Management Command and Control
EscaPADE	Escape and Plasma Acceleration and Dynamics Explorers
ESD	Exploration Systems Development; Earth Science Division
ESG	Expeditionary Strike Group
ESIM	earth station in motion
ESM	European Service Module
ESP	Efficient Space Procurement; Environmental Studies Program
ESR	Emergency Stabilization and Rehabilitation
ESS	Evolved Strategic SATCOM
ET	evapotranspiration
ETM	Enhanced Thematic Mapper
EU	European Union
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
EUV	extreme ultraviolet
EVA	extravehicular activity
EVE	EUV Variability Experiment
EVER	Everglades National Park
EWPP-FPE	Emergency Watershed Protection Program–Floodplain Easements
EWS	Electro-optical/infrared Weather System
EWS-G	EWS-Geostationary
EXIM	Export-Import Bank
EXIS	EUV and X-ray Irradiance Sensor

F

FAA	Federal Aviation Administration
FAB-T	Family of Advanced Beyond-Line-of-Sight Terminals
FACA	Federal Advisory Committee Act
FARA	Future Attack Reconnaissance Aircraft
FAS	Foreign Agricultural Service
FAS/GMA	Foreign Agricultural Service/Global Market Analysis
FAS/OGA	Foreign Agricultural Service/Office of Global Analysis
FCC	Federal Communications Commission
FCIC	Federal Crop Insurance Corporation
FDSS	Faculty Development in Space Sciences
FEMA	Federal Emergency Management Agency
FES	Office of Fusion Energy Sciences
FGST	Fermi Gamma-ray Space Telescope
FHP	Forest Health Protection
FIA	Forest Inventory and Analysis
FLRAA	Future Long Range Assault Aircraft
FOC	Final Operational Capability
FORGE	Future Operationally Resilient Ground Evolution
FRP	Full Rate Production
FSA	Farm Service Agency
FSVeg Spatial	Field Sampled Vegetation
FTUAS	Future Tactical Unmanned Aerial Systems
FVEY	Five Eyes
FVL	Future Vertical Lift
FWS	Fish and Wildlife Service
FY	fiscal year

G

GADAS	Global Agricultural and Disaster Assessment System
GBD	Global Burst Detector
Gbps	gigabits per second
GDC	Geospace Dynamics Constellation
GEDI	Global Ecosystem Dynamics Investigation
G-EGD	Global Enhanced GEOINT Delivery
GEM	Geospace Environment Modeling
GEO	Geosynchronous Earth Orbit
GEO-AGS	Directorate for Geosciences' Division of Atmospheric and Geospace Sciences
GeV	gigaelectronvolt
GF	Geospace Facilities
GIS	geographic information system
GLAM	Global Agricultural Monitoring
G-LiHT	Goddard's Lidar, Hyperspectral, and Thermal Imager
GMT	Giant Magellan Telescope
GNSS	Global Navigation Satellite System
GOES	Geostationary Operational Environmental Satellite
GOES-T	Geostationary Operational Environmental Satellite–T
GONG	Global Oscillations Network Group
GPM	Global Precipitation Measurement
GPS	Global Positioning System
GPS IIIF	GPS III Follow-on
GPS SAR	GPS Search and Rescue
GPSC	Geospatial Products and Services Contract

G-REALM	Global Reservoir and Lake Monitor
GRC	Glenn Research Center
GS	Geospace Section
GUT	grand-unified theory

H

HALO	Habitation and Logistics Outpost
HEP	Office of High Energy Physics
HF	high-frequency
HFIR	High Flux Isotope Reactor
HFRP	Healthy Forest Reserve Program
HLS	Human Landing System
HPD	Heliophysics Division
HPTC	high-pressure transcritical combustion
HRP	Human Research Program
HTV	H-II Transfer Vehicle

I

IAC	International Astronautical Congress
IAWN	International Asteroid Warning Network
IBEX	Interstellar Boundary Explorer
IC	Intelligence Community
ICAO	International Civil Aviation Organization
ICESat-2	Ice, Cloud and land Elevation Satellite–2
ICNO	IceCube Neutrino Observatory
ICPS	Interim Cryogenic Propulsion Stage
IDA	international docking adapter
IDEX	International Defence Exhibition and Conference
IfSAR	Interferometric Synthetic Aperture Radar
ILLUMA-T	Integrated LCRD Low-Earth Orbit User Modem and Amplifier Terminal
IMAP	Interstellar Mapping and Acceleration Probe
IMPRESS	IMpulsive Phase Rapid Energetic Solar Spectrometer
IMS	Interactive Multisensor Snow and Ice Mapping System
INL	Idaho National Laboratory
InSight	Interior Exploration using Seismic Investigations, Geodesy and Heat Transport
IOAG	Interagency Operations Advisory Group
IOC	Initial Operational Capability
IOP	Interoperability Plenary
IPAD	International Production Assessment Division
IR	infrared
IRAC	infrared array camera
IRIS	Interface Region Imaging Spectrograph
IRMA	Integrated Resource Management Applications
IRS-2	Indian Resourcesat–2
ISARA	Integrated Solar Array and Reflectarray Antenna
ISIL, ISIS	Islamic State
ISP	In Space Propulsion
ISR	Intelligence, Surveillance, and Reconnaissance
ISR&T	Intelligence, Surveillance, Reconnaissance, and Targeting
ISRU	In-Situ Resource Utilization
ISS	International Space Station
IT	Information Technology
IT&C	Integration, Testing and Commissioning

ITA	International Trade Administration
ITAC 1	Industry Trade Advisory Committee on Aerospace Equipment
ITE	Improved Turbine Engine
IVM	Ion Velocity Meter
IXPE	Imaging X-Ray Polarimetry Explorer

J

JAGM	Joint Air-to-Ground Missile
JASD	Joint Agency Satellite Division
JAXA	Japan Aerospace Exploration Agency
JFMCC	Joint Forces Maritime Component Commander
JMR-TD	Joint Multi-Role Technology Demonstrator
JPL	Jet Propulsion Laboratory
JPSS	Joint Polar Satellite System
JSC	Johnson Space Center
JUICE	Jupiter Icy Moons Explorer
JWST	James Webb Space Telescope

K

K-T	Cretaceous-Tertiary
KRUSTY	Kilopower Reactor Using Stirling Technology
KSC	Kennedy Space Center

L

LAANC	Low Altitude Authorization and Notification Capability
LANL	Los Alamos National Laboratory
LAS	Launch Abort System
LASP	Laboratory of Atmospheric and Space Physics
LAT	Large Area Telescope
LCMAP	Land Change Monitoring, Assessment, and Projection
LCMS	Landscape Change Monitoring System
LCRD	Laser Communication Relay Demonstration
LDB	Long Duration Balloon Program
LEO	low-Earth orbit
lidar	light detection and ranging
LIGO	Laser Interferometer Gravitational-Wave Observatory
LIMWS	Limited Interim Missile Warning System
LIS	Lightning Imaging Sensor
LISS	Linear Imaging Self Scanning
LiteBIRD	Lite satellite for the studies of B-mode polarization and Inflation from cosmic background Radiation Detection
LLNL	Lawrence Livermore National Laboratory
LORRI	Long-Range Reconnaissance Imager
LRA	Laser Retro-reflector Array
LRASM	Long-Range Anti-Ship Missile
LRIP	Low-Rate Initial Production
LRO	Lunar Reconnaissance Orbiter
LSA	Launch Service Agreement
LSFR	Little Saint Francis River Chat Pile
LSP	Launch Services Program; Launch Service Procurement
LSST	Large Synoptic Survey Telescope
LST	Land Surface Temperature

LTS	Long-Term Sustainability
LUSI	Lunar Spectral Irradiance
LVSA	Launch Vehicle Stage Adapter

M

MANPADS	Man Portable Air Defense Systems
MarCO	Mars Cube One
MBTA	Migratory Bird Treaty Act
MDO	Multi-Domain Operations
MDXR	Missile Defense Transfer Radiometer
MEDLI2	Mars Entry, Descent and Landing Instrumentation 2
MEF	Marine Expeditionary Force
MEO	Medium-Earth Orbit
MEOSAR	Medium Earth Orbit Search and Rescue
MEP	Manufacturing Extension Partnership
MER	Mars Exploration Rover
MEV	Mission Extension Vehicle
MGUE	Military GPS User Equipment
MIDEX	Medium-Class Explorer
MIT	Massachusetts Institute of Technology
MKID	microwave kinetic-inductance detector
ML	Mobile Launcher
MMPA	Marine Mammal Protection Act
MMRTG	multi-mission radioisotope thermoelectric generator
MMS	Magnetospheric Multiscale
MOBY	Marine Optical Buoy
MODIS	Moderate Resolution Imaging Spectroradiometer
MOSA	Modular Open System Architecture
MOU	Memorandum of Understanding
mph	miles per hour
MPRF	Maritime Patrol and Reconnaissance Force
MPS	Mathematical and Physical Sciences Directorate
MRI	Magnetic Resonance Imaging
MRO	Mars Reconnaissance Orbiter
MRX	Magnetic Reconnection Experiment
MSFC	Marshall Space Flight Center
MSIP	Mid-Scale Innovations Program
MTA	Middle Tier of Acquisition
MTBS	Monitoring Trends in Burn Severity
Multi-Int	multiple intelligence

N

NAC	NextGen Advisory Committee
NAICS	North American Industry Classification System
NAIP	National Agriculture Imagery Program
NANOGrav	North American Nanohertz Observatory for Gravitational Waves
NAS	Naval Air Station; National Airspace System; National Academy of Sciences
NASM	National Air and Space Museum
NASS	National Agricultural Statistics Service
NATO	North Atlantic Treaty Organization
NBR	Normalized Burn Ratio
NDAA	National Defense Authorization Act
NDOP	National Digital Orthoimagery Program

NDVI	Normalized Difference Vegetation Index
NE	Office of Nuclear Energy
NEFSC	Northeast Fisheries Science Center
NEK	Nezemnyy Eksperimental'nyy Kompleks
NEN	Near Earth Network
NEO	near-Earth object
NEPA	National Environmental Policy Act
NERSC	National Energy Research Supercomputing Center
NeXT	Neutron/X-Ray Tomography
NextGen	Next Generation Air Transportation System
Next-Gen OPIR	Next Generation Overhead Persistent Infrared
NextSTEP	Next Space Technologies for Exploration Partnerships
NFS	National Forest System
NGA	National Geospatial-Intelligence Agency
NGEE	Next Generation Ecosystem Experiment
NGLAW	Next Generation Land Attack Weapon
NGMS	Northrop Grumman Mission Systems
NGO	nongovernmental organization
NGSC	Next Generation Strike Capability
NIAC	NASA Innovative Advanced Concepts
NISAR	NASA–Indian Space Research Organization Synthetic Aperture Radar
NIST	National Institute of Standards and Technology
NLCD	National Land Cover Database
NMFS	National Marine Fisheries Service
NMNH	National Museum of Natural History
NNSA	National Nuclear Security Administration
NOAA	National Oceanic and Atmospheric Administration
NOAO	National Optical Astronomy Observatory
NOC	National Operations Center
NP	Office of Nuclear Physics
NPS	National Park Service
NRAO	National Radio Astronomy Observatory
NRC Canada	National Research Council Canada
NRCS	Natural Resources Conservation Service
NRHO	near-rectilinear halo orbit
NRI	National Resources Inventory
NRL	Naval Research Laboratory
NRO	National Reconnaissance Office
NROL	National Reconnaissance Office Launch
NRPP	Natural Resources Preservation Project
NSF	National Science Foundation
NSO	National Solar Observatory
NSpC	National Space Council
NSPO	National Space Organization
NSRL	NASA Space Radiation Laboratory
NSS	National Security Space
NSSL	National Security Space Launch
NSTC	National Science and Technology Council
NSW	Navy Special Warfare
NSW-SAP	National Space Weather Strategy and Action Plan
NSWAP	National Space Weather Action Plan
NSWP	National Space Weather Program
NSWS	National Space Weather Strategy
NTIA	National Telecommunications and Information Administration
NTP	Nuclear Thermal Propulsion

NWP	numerical weather prediction

O

O3	third observational run
OCO	Orbiting Carbon Observatory
OCONUS	Outside CONUS
OCS	Outer Continental Shelf
OCSD	Optical Communications and Sensor Demonstration
OCX	Operational Control System
ODNI	Office of the Director of National Intelligence
OECD	Organization for Economic Cooperation and Development
OEM	Original Equipment Manufacturer
OES/SAT	Bureau of Oceans and International Environmental and Scientific Affairs/Office of Space and Advanced Technology
OFII	Office of Finance and Insurance Industries
OFT	Orbital Test Flight
OLI	Operational Land Imager
OMS	Orbital Micro Systems
OPP	Office of Polar Programs
ORI	orthorectified radar intensity image
ORNL	Oak Ridge National Laboratory
ORR	Operations Readiness Review
OSA	Orion Stage Adapter
OSIRIS-REx	Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer
OTAP	On Time As Promised
OTM	Office of Transportation and Machinery

P

P&E	Plant and Equipment
P&P	Products and Processes
PACE	Plankton, Aerosol, Clouds, and ocean Ecosystem
PBN	Performance Based Navigation
PBS	Plum Brook Station
PEO	Program Executive Office
PeV	petaelectronvolt
PHY	Division of Physics
PI	Principal Investigator
PICASSO	Planetary Instrument Concepts for the Advancement of Solar System Observations
PML	Physical Measurement Laboratory
PNT	Positioning, Navigation, and Timing
POES	Polar-orbiting Operational Environmental Satellites
PONDS	Passive Orbital Nutrient Delivery System
POR	Program of Record
PPE	Power and Propulsion Element
PPPL	Princeton Plasma Physics Laboratory
PREEVENTS	Prediction and Resilience against Extreme Events
PRISM	Parameter-elevation Regressions on Independent Slopes Model
PSD	Planetary Science Division; production, supply, and distribution
PTES	Protected Tactical Enterprise Service
PTS	Protected Tactical SATCOM
Pu	plutonium
PUFFER	Pop-Up Flat-Folding Explorer Robot

Q

QAQC	quality assurance and quality control
QueSST	Quiet SuperSonic Technology

R

RAWS	Remote Automated Weather Station
RECOVER	Rehabilitation Capability Convergence for Ecosystem Recovery
RF	Radio Frequency
RFB	Radio Frequency Beacon
RFI	request for information
RFP	request for proposals
RHIC	Relativistic Heavy Ion Collider
RMA	Risk Management Agency
RMSE	root mean square error
RNAV	Area Navigation
RNP	Required Navigation Performance
RO	radio occultation
ROI	Return on Investment
ROSES	Research Opportunities in Space and Earth Sciences
RPS	Radioisotope Power Systems
RPT	Rocket Propulsion Testing
RR	Rodent Research
RSCC	Remote Sensing Coordinating Committee
RSLP	Rocket Systems Launch Program
RSTA	Reconnaissance, Surveillance, and Target Acquisition
RTK	Real Time Kinematic
RTK GPS	Real-Time Kinematic Global Positional System

S

SABRS	Space and Atmospheric Burst Reporting System
SAE	Society of Automotive Engineers
SAM	Spacecraft Atmosphere Monitor
SAO	Smithsonian Astrophysical Observatory
SAR	Synthetic Aperture Radar
SATCOM	Satellite Communications
SBEM	Space Based Environmental Monitoring
SBIR	Small Business Innovative Research
SBIRS	Space Based Infrared System
SC	Office of Science
SCALE	Shared Cognitive Architectures for Long-term Exploration
SCaN	Space Communications and Navigation
SCAN	Soil Climate
SCLT	Systems Capability Leadership Team
SCS	Soil Conservation Service
SDB II	Small Diameter Bomb II
SDI	Space Data Integrator
SDO	Solar Dynamics Observatory
SEACS	suitably equipped air capable ships
SEIS	Seismic Experiment for Interior Structure
SEM	Space Environment Monitor
SERB	Space Experiments Review Board
SET	Space Environment Testbeds

SFA	Space Framework
SfM	structure-from-motion
SFS	Space and Flight Support
SFWMD	South Florida Water Management District
SGSS	Space Network Ground Segment Sustainment
S.H.E.	Soaring Higher Explorers
SHIIVER	Structural Heat Intercept, Insulation and Vibration Evaluation Rig
SI	International System of Units
SIA	Satellite Imagery Archive
SLPSRA	Space Life and Physical Sciences Research and Applications
SLS	Space Launch System
SMAP	Soil Moisture Active Passive
SMC	Space and Missile Systems Center
SMD	Science Mission Directorate
SMPAG	Space Mission Planning Advisory Group
SN	Space Network
SNF	Superior National Forest
SNL	Sandia National Laboratories
SNOTEL	Snow Survey Telemetry
SNSPD	superconducting nanowire single-photon detector
SO_2	sulfur dioxide
SOC	Space Optical Clock
SpaceX	Space Exploration Technologies
SPD	Space Policy Directive; supersonic particle deposition
Spectrum	Spectrum Multi-Fluorescence Spectral Imager
SPHEREx	Spectro-Photometer for the History of the Universe, Epoch of Reionization and Ices Explorer
SPLICE	Safe and Precise Landing—Integrated Capabilities Evolution
SpRCO	Space Rapid Capabilities Office
SPT	South Pole Telescope
SPUD	Small Polarimeter Upgrade for Degree Angular Scale Interferometer
SQUID	superconducting quantum interference device
SSA	Space Situational Awareness
SSAEM	Space Situational Awareness Environmental Monitoring
SSDP	Space Security and Defense Program
SSMIS	Special Sensor Microwave Imager/Sounder
SSN	Space Surveillance Network
SSTI	Small Spacecraft Technology Initiative
SSV	Space Service Volume
STARS	Standard Terminal Automation Replacement System
STDT	Science and Technology Definition Team
STEM	science, technology, engineering, and mathematics
STMD	Space Technology Mission Directorate
STP	Space Test Program
STR	Solar-Terrestrial Research
STS	Space Transportation System
STTR	Small Business Technology Transfer
sUAS	small Unmanned Aerial Systems
Suomi NPP	Suomi National Polar-orbiting Partnership
SURF	Synchrotron Ultraviolet Radiation Facility
SVC	System Vicarious Calibration
SWARM-EX	Space Weather Atmospheric Reconfigurable Multiscale Experiment
SWIM	System Wide Information Management
SWORM	Space Weather Operations, Research, and Mitigation
SWR	Space Weather Research
SwRI	Southwest Research Institute

SWSH	Space Weather, Security, and Hazards
SWxSA	Space Weather Science Application
SynBio	Space Synthetic Biology

T

TACTOM	Tactical Tomahawk
TAMR	Terminal Automation Modernization and Replacement
TBFM	Time Based Flow Management
TBO	Trajectory Based Operations
TCC	Tree Canopy Cover
TCL	Technical Capability Level
TDRS	Tracking and Data Relay Satellite
TEMPO	Tropospheric Emissions: Monitoring Pollution
TES	transition-edge sensor; Terrestrial Ecosystem Science
TESS	Transiting Exoplanet Survey Satellite
TFDM	Terminal Flight Data Manager
TFMS	Traffic Flow Management System
TFRSAC	Tactical Fire Remote Sensing Advisory Committee
TGRS	Tri-GNSS Radio occultation System
THEMIS	Time History of Events and Macroscale Interactions during Substorms
TIA	Technology Investment Agreement
TLS	terrestrial laser scanning
TM	Thematic Mapper
TNMCorps	The National Map Corps
TOI	TESS Object of Interest
TOPEX	Ocean Topography Experiment
TRACON	terminal radar approach control
Tri-GNSS	Tri-Global Navigation Satellite System
TRISH	Translational Research Institute for Space Health
TRN	terrain relative navigation
TSAS	Terminal Sequencing and Spacing
TT&C	telemetry, tracking, and communication
TTPs	Tactics, Techniques and Procedures

U

UAG	Users' Advisory Group
UAS	Unmanned Aircraft Systems; Unmanned Aerial Systems
UAS EXCOM	UAS Executive Committee
UAS SSG	UAS Senior Steering Group
UASSC	Unmanned Aircraft Systems Standards Collaborative
UAV	Unmanned Aerial Vehicle
UCAR	University Corporation for Atmospheric Research
ULA	United Launch Alliance
ULI	University Leadership Initiative
UN	United Nations
UNGA	UN General Assembly
UNOOSA	UN Office for Outer Space Affairs
URT	Underway Recovery Test
USACE	U.S. Army Corps of Engineers
USAF	U.S. Air Force
USDA	U.S. Department of Agriculture
USFS	U.S. Forest Service
USGS	U.S. Geological Survey

USMC	U.S. Marine Corps
USN	U.S. Navy
USNDS	U.S. Nuclear Detonation Detection System
UTM	Unmanned Aircraft Systems Traffic Management
UV	ultraviolet
UWMS	Universal Waste Management System
UXR	User Transfer Radiometer

V

VBI	Visible Broadband Imager
VCLS	Venture Class Launch Services
VERITAS	Very Energetic Radiation Imaging Telescope Array System
VHF	Very High Frequency
VIIRS	Visible Infrared Imaging Radiometer Suite
VISORS	Virtual Super-resolution Optics with Reconfigurable Swarms
VLF	Very Low Frequency
VMI	Vegetation Mapping Inventory
VSWIR	visible to shortwave-infrared

W

WAAS	Wide Area Augmentation Service
WAOB	World Agricultural Outlook Board
WASDE	World Agricultural Supply and Demand Estimates
WFC	Wave Front Correction
WGS	Wideband Global SATCOM
WIN	Written Impact Narratives
WiPPL	Wisconsin Plasma Physics Laboratory
WRC	World Radiocommunication Conference
WSF	Weather System Follow-on
WSF-M	WSF-Microwave
WSTF	White Sands Test Facility

X

XVS	eXternal Vision System

NP-2020-05-2851-HQ