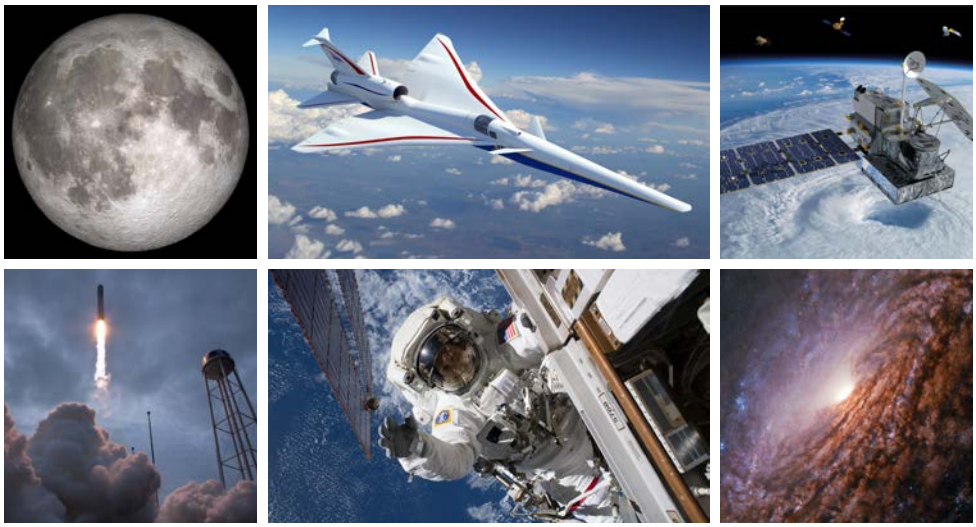
Aeronautics and Space Report of the President

Fiscal Year 2018 Activities



Aeronautics and Space Report
OF THE PRESIDENT

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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, 2017, through September 30, 2018. 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.** Image of the full moon with topographical shadows added using elevation data derived from measurements by the Lunar Orbiter Laser Altimeter (LOLA) aboard the Lunar Reconnaissance Orbiter (LRO). Credit: NASA/Goddard Space Flight Center Scientific Visualization Studio. **2.** Artist's concept of NASA's X-59 Quiet Supersonic Technology Low-Boom Flight (QueSST) Demonstrator in flight. Credit: NASA/Lockheed Martin. **3.** The Global Precipitation Measurement (GPM) Core Observatory, launched in 2014, is a joint international project with the Japan Aerospace Exploration Agency (JAXA). It is part of an international satellite constellation producing global observations of rainfall and snowfall. Credit: NASA. **4.** The unbarred spiral galaxy NGC 5033, located about 40 million light-years away in the constellation of Canes Venatici (The Hunting Dogs). Credit: Hubble/European Space Agency (ESA). **5.** On June 14, 2018, Ricky Arnold, pictured here, and Station Commander Drew Feustel completed the sixth spacewalk at the International Space Station in 2018. Credit: NASA **6**. The Orbital ATK Antares rocket, with the Cygnus spacecraft onboard, launches from Pad-0A, Sunday, November 12, 2017, at NASA's Wallops Flight Facility in Virginia. Credit: NASA/Bill Ingalls.

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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 and fostered close coordination and cooperation among the domestic civil, national security, and commercial space sectors, as well as advising on international space activities. The Council's Chair, Vice President Mike Pence, is supported by the National Space Council members, which include the heads of the agencies, offices, and departments responsible for the United States space enterprise.

The Council held its first meeting on October 5, 2017, at the Smithsonian National Air and Space Museum's Steven F. Udvar-Hazy Center in Chantilly, Virginia. At the meeting, Vice President Mike Pence articulated the Administration's direction for space exploration, and the Council adopted a recommendation to the President to return American astronauts to the Moon, and then send crewed mission to Mars and other destinations. Space Policy Directive–1, signed by President Donald Trump on December 11, 2017, adopted this recommendation, calling for "an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities."

The Council met again on February 21, 2018, at the Space Station Processing Facility at the John F. Kennedy Space Center on Merritt Island, Florida. This meeting resulted in four recommendations focusing on regulatory reform to advance the commercial space industry. In an effort to modernize existing regulatory frameworks, Space Policy Directive–2, signed by President Trump on May 24, 2018, directs the transformation of launch and reentry licensing for spacecraft; the elevation of space functions within the Department of Commerce; the review of a wide

variety of new issues to enable efficient and predictable regulation of space activities; the protection of radiofrequency spectrum for space activities; and an update to commercial space-related export controls.

The Council met for a third time on June 18, 2018, in the East Room of the White House, where the Council adopted a recommendation to change the way that space traffic management is conducted in the United States. Space Policy Directive–3, signed at the third meeting of the Council, was issued to address the challenges of operating in a congested space environment by establishing clear roles and responsibilities for U.S. Government departments and agencies. The foundational principles of the new space traffic management policy include safety, stability, and sustainability; timely and actionable space situational awareness data; accessible data and user interface; and a framework that consists of best practices, technical guidelines, safety standards, behavioral norms, pre-launch risk assessments, and on-orbit collision avoidance services.

On February 18, 2018, it was announced that the Council would be supported by a Users' Advisory Group comprised of non-federal senior leaders from industry, academia, and other non-governmental organizations. The Users' Advisory Group met for the first time on June 19, 2018, to focus on strengthening public engagement, increasing commercialization activities in low Earth orbit, accelerating a return to the moon, identifying opportunities for international cooperation, and strengthening the relationship between science and exploration. The Users' Advisory Group has established 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.

National Aeronautics and Space Administration

NASA

Human Exploration and Operations Mission Directorate

Exploration Systems Development

The Exploration Systems Development (ESD) programs—Space Launch System (SLS), Orion, and Exploration Ground Systems (EGS)—continue 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. Exploration Mission–1 (EM-1) will be the first integrated test of Orion, SLS, and the supporting ground systems launching from Kennedy Space Center (KSC) in Cape Canaveral, Florida, in 2020 (date under review) and will pave the road for future missions with astronauts.

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 has completed the majority of the work to assemble the EM-1 crew module. Thousands of components like Orion's windows, avionics, wire

harnessing, and parachutes, which make up more than 30 subsystems, have been integrated and tested through evaluations like thermal cycle testing, proof tests on propulsion lines, and functional tests to ensure that systems work as planned. The team recently installed the heat shield that will protect the EM-1 crew module upon reentry from the lunar vicinity through Earth's atmosphere.

Testing on a structural test article in Denver for sound and vibration evaluations has confirmed that Orion can withstand the extreme acoustic and vibration environments of the launch and separation event in space. At sea, NASA and the Department of Defense (DOD) have honed the procedures and skills they will use to recover Orion upon splashdown in the Pacific Ocean. Flight controllers also conducted tests to ensure that Orion can communicate with Mission Control through NASA's satellite network. Welding of the Orion Exploration Mission–2 (EM-2) crew module pressure vessel was completed at Michoud Assembly Facility (MAF), and the assembly has been shipped to KSC for outfitting.

The Agency tested Orion's parachute system for the final time in mid-September 2018, bringing NASA another step closer to verifying that the spacecraft is ready to bring crews home in any scenario. Work is progressing at several NASA Centers in preparation for a test of Orion's launch abort system in the summer of 2019 that will verify that the crew can be carried to safety in an emergency during launch.

Space Launch System

The SLS is the most powerful, most capable launch system in the history of spaceflight. NASA is designing and implementing a manufacturing capability to efficiently produce, test, and qualify spaceflight hardware for long-term use, to human-rating standards, on a scale never achieved before, and this work represents a national investment in a long-term commitment to deep space exploration.

This year, NASA's Super Guppy aircraft delivered the EM-1 Orion stage adapter, the second of five major elements of the first SLS flight vehicle, to KSC. At MAF, the five major structural pieces of the SLS core stage are completing final outfitting and assembly. Construction of the forward skirt and intertank are complete, and the liquid-oxygen and -hydrogen tanks are nearing completion. The structural test

article for the hydrogen tank is planned to be completed by the end of the calendar year and will be ready for shipment to Marshall Space Flight Center (MSFC) for testing that will simulate the forces of flight. Structural qualification testing of the engine section was completed some time ago, and intertank structural qualification is under way. Teams have also been applying the thermal insulation to flight hardware for protection from the extreme temperatures it will face during launch. Improvements to the application process are reducing the time needed for this work.

The SLS team is putting the finishing touches on the 30-foot-tall launch vehicle stage adapter that will connect the core stage to the interim cryogenic propulsion stage, which was delivered to KSC last year. All four EM-1 RS-25 core stage engines are complete and ready for shipping to MAF for integration with the EM-1 core stage. The SLS booster team in Utah has finished nine of the ten EM-1 solid rocket motor segments. EM-2 flight hardware fabrication and assembly are also well under way on the SLS core stage, boosters, and core-stage engines. The liquid engines team is green-run hot fire testing engine controllers to be used as far out as the fourth flight of SLS, as well as testing new hardware made with advanced manufacturing technologies that will reduce engine costs by better than 33 percent.

Exploration Ground Systems

The Exploration Ground Systems Program is responsible for overseeing ground systems upgrades and modifications to support the launch of the SLS and Orion spacecraft for EM-1, deep space missions, and NASA's journey to Mars.

During 2018, major critical launch infrastructure neared completion in preparation for launch. EGS completed construction on the main flame deflector at the launch pad, and launch control teams conducted realistic launch simulations. Over the summer, software teams completed critical updates to use for command and control from the firing room to support the first mission.

In August 2018, EGS installed the final umbilical on the mobile launcher. In September 2018, for the first time since the mobile launcher was modified for the SLS, the massive tower rolled out atop the Crawler-Transporter 2 to Launch Pad 39B for a fit check that verified all physical connections between the launcher and

pad systems before rolling into the Vehicle Assembly Building for further analysis and detailed adjustments.

Commercial Crew Program

During FY 2018, NASA, Boeing, and SpaceX continued making technical and programmatic progress in maturing and certifying our partners' commercial crew transportation systems. This year has seen our commercial partners transition from final systems design and development efforts to flight hardware production, certification, and final acceptance testing as both partners prepare for their demonstration flights and Post Certification Mission (PCM) flights to the International Space Station (ISS). Boeing, SpaceX, and NASA continue to work issues identified during testing as both partners move closer to flight.

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 and ground infrastructure are in final work or have been completed, including the manufacture of spacecraft and launch vehicles and key ground systems, such as crew access arms required for crew ingress prior to launch.

Boeing completed several critical programmatic and technical milestones during FY 2018, including Integrated Parachute System Drop Tests 1 and 2, the start of ISS Software NASA Docking System (NDS) test development, the completion of Crew Seat Incline, NDS range-of-motion test, and Orbital Flight Test (OFT) Flight Operations Review (FOR).

SpaceX completed several programmatic and technical milestones during FY 2018, including the Demo-1 Dragon Integration Checkpoint; the Certification Checkpoint; the Integrated System Review, Phase II, Hazard Reports Checkpoint; Parachute Qualification, Part 1; the F9 Launch Vehicle Integration Review; and the Merlin Engine Qualification Checkpoint.

Through the Commercial Crew Program, 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 vehicle, 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 continue making technical and programmatic progress in maturing their respective commercial space capabilities.

International Space Station

The International Space Station continued its focus on research and technology development in such disciplines as biology, human research, biotechnology, Earth science, physical science, and astrophysics during FY 2018. Enabling such research are frequent Commercial Resupply Services (CRS) flights from Northrop Grumman (formerly Orbital ATK) and SpaceX. Prior to Northrop Grumman's purchase of Orbital ATK, Orbital ATK completed two cargo flights, and SpaceX completed three cargo flights to the ISS. In June 2018, Northrop Grumman completed its purchase of Orbital ATK, creating a new business unit named Northrop Grumman Innovation Systems. These cargo missions were complemented by those of our International Partners, particularly Roscosmos, which provided three Progress cargo missions, and the Japan Aerospace Exploration Agency (JAXA), which was responsible for the H-II Transfer Vehicle (HTV-7) mission during FY 2018. Additionally, NASA and Bigelow Aerospace extended Bigelow Expandable Activity Module (BEAM) presence on the ISS in order to provide additional performance data on expandable habitat technologies and enable new technology demonstrations. The module will also increase onboard stowage capability.

Three Soyuz crew rotation missions were accomplished in FY 2018. The departure of Soyuz 51S in December 2017 marked the end of Expedition 53. Their time aboard marked the first long-term increase in crew size on the U.S. segment of the ISS from three to four, allowing NASA to maximize time dedicated to research on the Station. Less than a week after the 51S crew landed, Soyuz 53S and the remaining members of Expedition 54 arrived on the ISS. This crew continued the long-term increase in crew size on the U.S. segment, enabling NASA to double the

time dedicated to research and achieve a record-setting week of research that surpassed 100 hours. Through the end of Expedition 54 (February 2018), the ISS had hosted over 2,500 investigations from more than 105 countries/areas. Soyuz 54S and 55S docked to the Station in March and June 2018 respectively. Expeditions 55 and 56 (which ended October 4, 2018) marked the completion of NASA's Year of Education on Station. In that timeframe, the ISS crew reached more than 200,000 students in 29 states.

Eight U.S. extravehicular activities (EVAs) were conducted during FY 2018. A trio of EVAs in October 2017 successfully replaced and lubricated one of two Latching End Effectors (LEEs) on the Station's robotic arm, Canadarm2, as well as removing and replacing the arm's camera system. The two end effectors on each end of the arm are used as "hands" to grapple visiting vehicles (such as Dragon) and components during a variety of operational activities. The next pair of EVAs, on January 23 and February 16, 2018, respectively, replaced another LEE each and installed them in their long-term operational locations. An EVA in March 2018 installed wireless communications antennas and removed hoses from a cooling system. U.S. EVA #50 in May 2018 moved the Pump Flow Control Subassembly (PFCS) from a spare parts platform on the Station's truss to the Special Purpose Dexterous Manipulator (also known as Dextre), a maintenance robot that can be attached to Canadarm2. The PFCS controls the flow of ammonia through the exterior portions of the Station's cooling system. In June 2018, the final spacewalk of FY 2018 successfully installed new high-definition cameras that will provide enhanced views during the final phase of approach and docking of the SpaceX Crew Dragon and Boeing Starliner commercial crew spacecraft that will soon begin launching from American soil.

Orbital ATK's eighth contracted cargo mission, OA-8, arrived at the ISS on November 14, 2017, following a November 12 launch on an Antares rocket from the Mid-Atlantic Regional Spaceport, a complex owned by the state of Virginia at NASA's Wallops Flight Facility. The Cygnus spacecraft delivered over 7,400 pounds of crew supplies, science experiments, spacewalk gear, Station hardware, and computer parts. Some of the research payloads delivered investigated the space impacts on microbiology and botany. The advanced space research will explore the effectiveness of antibiotics on astronauts and observe how plants absorb nutrients in microgravity.

Orbital ATK launched its ninth contracted cargo mission, OA-9, to the ISS on May 21, 2018. The Cygnus spacecraft, carrying 7,400 pounds of cargo, was berthed at the ISS three days later. During Cygnus approach, it became the first spacecraft to use the new Common Communications for Visiting Vehicles (C2V2). This communication system unifies all communications through a single system and provide a more reliable communication link for future cargo and commercial vehicles. In addition to delivering a variety of research investigations, the Cygnus vehicle also performed a thruster firing to increase the Station's altitude. This was the first reboost of the ISS by a U.S. spacecraft since the retirement of the Space Shuttle.

SpaceX launched its 13th contracted cargo mission, SpX-13, to the ISS on December 15, 2017. The Dragon spacecraft was successfully berthed to the ISS on December 17, 2017. This commercial resupply mission delivered more than 4,800 pounds of supplies and payloads to the Station. Among the research materials delivered was an investigation demonstrating the benefits of manufacturing fiber optic filaments in a microgravity environment. Designed by the company Made in Space, and sponsored by the Center for the Advancement of Science in Space (CASIS), the investigation pulled fiber-optic wire from ZBLAN, a heavy-metal fluoride glass commonly used to make fiber-optic glass. Results from this investigation could lead to the production of higher-quality fiber-optic products for use in space and on Earth. The Dragon spacecraft departed the Station on January 13, 2018, and returned to Earth with nearly 4,100 pounds of research, hardware, and crew supplies.

Two days after its launch from Florida on April 2, 2018, the SpaceX-14 mission's Dragon cargo spacecraft was grappled and berthed on the Harmony module of the ISS. This 14th contracted commercial resupply mission delivered about 5,800 pounds of cargo to the ISS. Among the research arriving for the U.S. National Laboratory was a Metabolic Tracking investigation to evaluate the use of a new method to test, in microgravity, the metabolic impacts of pharmaceutical drugs. This work could lead to more-effective, less-expensive medicines on Earth. The Multi-use Variable-g Platform (MVP) will serve as a new test bed aboard the Space Station, able to host 12 separate experiment modules with samples such as plants, cells, protein crystals, and fruit flies. The Center for the Advancement of Science in Space (CASIS), which manages the U.S. National Laboratory,

sponsored the investigation and the MVP. Dragon remained attached to the ISS until May 5, when it returned to Earth with more than 4,000 pounds of cargo.

A SpaceX-15 Falcon 9 rocket launched from Space Launch Complex 40 at Cape Canaveral Air Force Station in Florida on June 29, 2018, with more than 5,900 pounds of research, equipment, cargo, and supplies that supported dozens of investigations aboard the orbiting laboratory. Among the cargo was a spare Latching End Effector. This was the 30th grapple of an arriving spacecraft and the 15th time the Canadarm2 has captured a Dragon. Among the research arriving on Dragon was a cellular biology investigation (Micro-12) to understand how microgravity affects the growth, gene expression, and ability of a model bacterium to transfer electrons through its cell membrane along the bacterial nanowires it produces. Such bacteria could be used in microbial fuel cells to make electricity from waste organic material. Additionally, an Earth science instrument called the ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) was delivered with expectations to provide a new space-based measurement of how plants respond to changes in water availability. These data can help society better manage agricultural water use.

The HTV-7 cargo mission was launched from the Tanegashima Space Center in southern Japan on September 22, 2018, and was berthed to the ISS five days later. The cargo spacecraft began its trip to the orbiting laboratory with a launch on an H-IIB rocket from the Tanegashima Space Center. The cargo delivery includes more than five tons of supplies, water, spare parts, and experiments for the crew aboard the ISS. The spacecraft also carried a half dozen new lithium-ion batteries to continue upgrades to the Station's power system. After its release in early FY 2019, a new, small reentry capsule was deployed from the unpiloted HTV-7 vehicle. The conically shaped capsule was a technology demonstration designed to test JAXA's ability to return small payloads from the Station for expedited delivery to researchers.

Space Life and Physical Sciences Research and Applications (SLPSRA)

Human Research Program (HRP)

In 2018, NASA sponsored research to mitigate human health and performance risks associated with long-duration spaceflight. NASA ISS crewmembers

conducted 11 biomedical investigations during each of the ISS mission increments; completed three major ISS flight investigations; initiated six new flight investigations; and continued two ongoing investigations that included pre-flight baseline data collection, in-flight ISS data collection, and post-flight data collection as required. These long-duration spaceflight studies included research on standardized behavioral measures for detecting potential behavioral health risks during future exploration missions, assessment of exploration food technology for long-term food stowage and fresh food production, and physiological research on vertebral strength and injury risk. Additionally, NASA implemented the ISS Spaceflight Standard Measures project to collect a set of core measurements during and after long-duration ISS missions; these measurements can be used to study many of the astronaut health risks. The goal is to ensure that an optimized set of measures is consistently captured from all ISS crewmembers in order to characterize the health of a human in space in preparation for exploration missions.

NASA is continuing analysis of the ISS One-Year Mission and Twins Study data to support the future publication of research results in 2019. For more than a year, identical twin brothers Scott and Mark Kelly participated by providing physiological samples and performing psychological tests. For Scott, samples were collected before, during, and after his one-year ISS mission. This approach allowed for a more complete and accurate assessment of how genes may be expressed differently due to environmental factors over time during the year of spaceflight. This comprehensive biological, physiological, and psychological analysis will allow NASA to better understand the health risks associated with space travel and develop strategies to mitigate these risks. Further, NASA is also assessing ISS plans and recommendations regarding additional future One-Year Missions to gain a better understanding of the effects of these longer-duration spaceflights, as well as how to use the ISS as an exploration operational analog to assess the impacts of crew isolation during exploration missions.

NASA's Translational Research Institute for Space Health (TRISH), headquartered at Baylor College of Medicine in Houston, Texas, is charged with developing innovative approaches to reducing risks to humans during long-duration exploration missions. TRISH continued to solicit from the national biomedical research community's cutting-edge terrestrial research to translate their findings into

mitigation strategies for exploration missions. This translational interdisciplinary research model focuses on rapidly translating fundamental research concepts into practice, thereby generating tangible health outcomes—in this case, for astronauts. During 2018, TRISH identified biomedical innovations and has 22 projects selected through two research announcements: 1) Biomedical Research Advances for Space Health solicited six deep space–relevant topic areas and 2) the industry solicitation requested proposals from small U.S.-based companies for technologies essential for self-reliant healthcare in deep space. TRISH also initiated an industry-focused partnership with the Consortia for Improving Medicine with Innovation and Technology, solicited and funded outstanding postdoctoral fellows, and supported training for future NASA flight surgeons.

In 2018, the HRP completed the following key milestones:

- The Galactic Cosmic Ray (GCR) Simulator Project went operational at the NASA Space Radiation Laboratory at the Department of Energy's Brookhaven National Laboratory. NASA will use the GCR simulator to rapidly switch between ion species and energies, allowing for a more realistic simulation of the actual radiation environment found in space. This process will help NAS to better understand the radiation health risks to astronauts.
- The Effects of Isolation on Behavioral Health and Performance Project completed four 45-day isolation study campaigns using the Human Exploration Research Analog (HERA) facility located at NASA Johnson Space Center. HERA is a unique three-story habitat designed to serve as an analog for isolation, confinement, and remote conditions in exploration scenarios. Each HERA campaign puts crews of four through simulated deep space missions and is supported by a mission control team. A variety of experiments are conducted during each 45-day simulated mission. Additionally, NASA is continuing preparations for long-duration isolation and confinement studies at the Nazemnyy Eksperimental'nyy Kompleks (NEK) facility in Moscow, Russia, in collaboration with the Russian Academy of Sciences Institute for Biomedical Problems. The collaboration included a two-week SIRIUS-17 mission, which commenced in early FY 2018, to test the feasibility of systems in support of a longer four-month SIRIUS-18 mission, which will commence in the spring of 2019.

- The Advanced Twin Lifting and Aerobic System (ATLAS) Project completed the preliminary design review in preparation for the development and validation of a deep space exercise device on the ISS and is scheduled to be launched in the 2020 timeframe. 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. It meets aerobic and resistance exercise functional performance requirements needed to maintain crew health and performance for exploration missions, such as those envisioned for the Gateway and habitat concepts, and accomplishes this in an extremely compact footprint.

Biological and Physical Sciences (BPS)

Under the management of the Space Life and Physical Sciences Research and Applications 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.

SLPSRA has made several focused efforts to connect research it sponsors under the theme of Enabling Exploration with organizations responsible for integrating technologies into exploration missions. One such effort, the Zero Boil-Off Tank (ZBOT) experiment, is a research project developed and operated by SLPSRA on the ISS in 2018. It was identified by the Space Technology Mission Directorate as "Exploration Critical" in recognition of the value of the data from the experiment for the design of future cryogenic fuel storage facilities in space. ZBOT provided archival data for benchmarking and improving computational fluid dynamics (CFD) models and codes used by the cryogenic fluids management community and aerospace companies for future (ground-tested-only) tank designs.

SLPSRA research in 2018 is also part of NASA's commitment to develop the potential of low-Earth orbit (LEO) through pioneering scientific discovery. The continuing success of the ISS partnership hinges on NASA's continuing leadership in space research and development. An example of how SLPSRA work in

2018 helped maintain the vitality of the ISS partnership is in cold atom research. Working with a team of distinguished physicists that includes three Nobel Laureates, NASA is operating the Cold Atom Laboratory (CAL) on the ISS. In the weightless environment of the ISS, CAL is able to create the coldest atoms in the observable universe, atoms so cold and nearly motionless that, following the Uncertainty Principle, each atom will be almost observable with the naked eye. Physicists working in German laboratories have been using microgravity for several years now and have been eager to get access to facilities on the ISS. In 2018, the German Aerospace Center (DLR) and NASA have entered into an agreement that will see a German-developed follow-on to CAL on the ISS in the early 2020s. In 2018, a joint U.S.-German Science Definition Team defined the capabilities and technical objectives for the new facility, called Bose-Einstein Condensate Cold Atom Laboratory (BECCAL) at the System Concept and Requirements Review, an important early milestone in the development of the ISS payload. BECCAL will be an important contribution to the scientific productivity of the ISS for European and American scientists in the next decade of ISS operations.

Scientific discovery is also the pioneering effort for future commercial developments. Throughout the history of science, basic research has created opportunities for commercial application. In 2018, SLPSRA and CASIS, which manages the ISS National Laboratory, cosponsored the Advanced Colloids Experiment-Temperature-6 (ACE-T-6), which was led by a Principal Investigator employed by Proctor and Gamble and which studied the microscopic behavior of colloids in the absence of sedimentation effects in microgravity. This experiment provided new and valuable insights into fundamental interactions that can improve the shelf life of various products, such as paints, gels, and creams.

In 2018, NASA made significant progress to enable exploration in the area of space biology. The Micro-12 experiment was completed, advancing the potential use of bioelectrochemical systems for wastewater processing and synthesis of products such as biofuels, food products, and therapeutics on future long-duration missions. Use of bioelectrochemical systems for wastewater processing and product synthesis also has potential applications on Earth, particularly in remote and harsh environments or critical situations such as natural disasters.

A new series of Veggie experiments was conducted in 2018. The Veg-03 series expanded on previous validation tests to enable crew to grow cabbage, lettuce, and other fresh vegetables. Future long-duration missions will require a fresh food supply to supplement crew diets, which means growing crops in space. Tests determine which types of microorganisms are present in space-grown cabbage, providing baseline data for future crop-growing efforts. Behavioral health surveys assess the impact of growing plants on crew morale and mood.

The Rodent Research-7 (RR-7) experiment examined how the space environment affects the community of microorganisms in the gastrointestinal tract of mice (also known as the microbiome). It also looked at microgravity's effects on multiple physiological systems known to be affected by the microbiota, including the gastrointestinal, immune, metabolic, circadian, and sleep systems. Rodent Research-7 advanced knowledge of the role of gut microbiota in mammalian health and how spaceflight affects it over time. The study evaluates relationships between system changes such as sleep-wake cycle disruption and imbalance of microbial populations, identifying contributing factors and supporting the development of countermeasures to protect astronaut health during long-term missions. Many disorders of human gastrointestinal, immune, metabolic, and sleep systems on Earth are affected by a person's microbiota. The RR-7 investigation provides new insight to guide the development of interventions targeting an imbalance of microbial populations within the body.

The open science initiative, GeneLab, released version 2.0 of the publicly available data system. This 2018 release includes enhanced search capabilities, data federation, new metadata-tabbed user interfaces, a data-visualization dashboard, a collaborative workspace, and helpful user guides. GeneLab also formed Analysis Working Groups with researchers from around the country to best utilize the more than 200 datasets that are housed in the system. By using systems biology approaches to identify cross-species relevance, mechanisms, biomarkers, and potential health risks, GeneLab increases NASA's scientific return on investment by accelerating the pace of scientific discovery and enabling exploration and the development of countermeasures.

Human Spaceflight Capabilities

During FY 2018, Rocket Propulsion Testing (RPT) safely performed 1,056 tests of rocket engines and components at various levels of thrust. Hot fire test time totaled 12,765 seconds. In addition to the hot fire tests, RPT facilities performed 326 hours of thermal vacuum testing for vehicle certifications and facility checkouts in preparation for the vehicle certifications. These tests were completed with only seven facility-caused test delays, resulting in a 99.3 percent test stand availability, exceeding the Agency performance goal of 90 percent as defined in Space and Flight Support (SFS) section 15-1 of the NASA Management and Performance report.

RPT performed six RS-25 engine tests on the Stennis Space Center (SSC) A-1 test stand. The tests accounted for 2,209 seconds of hot fire test time in a multi-year effort to certify the engine for use on the SLS core booster stage. In addition to the RS-25 tests performed on the A-1 test stand, SSC performed ten tests within 240 hours in support of the Defense Advanced Research Projects Agency (DARPA) XSP program. Other test activities included testing support for SpaceX, Aerojet Rocketdyne, other NASA programs, and 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 component testing on E-1 Test Stand, Cell 2.

At the Johnson Space Center (JSC) White Sands Test Facility (WSTF), engineers conducted tests to support NASA's Orion and Commercial Crew Programs, 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 the European Space Agency [ESA]) and the Boeing CST-100 service module, the launch abort engines, the reaction control system, and the orbital maneuvering and attitude control thrusters.

At Glenn Research Center (GRC) Plum Brook Station (PBS), following refurbishment in 2017, the In Space Propulsion Facility (ISPF) validated the updated systems and performed the thermal vacuum certification testing for the Commercial

Crew Program SpaceX Dragon Crewed Capsule. RPT also continued collaborating with GRC to refurbish the ISPF to perform propulsion-related testing for systems of up to 30 kilopound-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 also pursued two initiatives to meet the changing needs of the propulsion systems developers. The first initiative is the development of two small test capabilities that can be operated with a minimum crew for development projects. The first of these test capabilities is the completion of a 5,000-pound-force portable test rig. The second capability is a collaborative initiative utilizing early-career engineers from the participating RPT centers to design and develop a larger 10,000- to 15,000-pound-force-thrust portable test capability. In addition to the chance to design a test capability, the early-career engineer initiative offers the participants an opportunity to gain critical experience in NASA's design processes, enhance communications skills, and build relationships amongst the Centers.

The second initiative being pursued by the RPT Program Office is the RPT Benchmarking Initiative for Test Efficiencies and Affordability. The goal is to identify best practices that could be implemented at the participating RPT centers to identify tangible changes that could improve RPT operational efficiencies and decrease costs for the RPT Program Office and for test customers.

Results of the benchmarking initiative will be used to assist in planning activities by the RPT Program to ensure that efficient and affordable RPT test services are available to current and future test customers.

Launch Services

The Launch Services Program (LSP) successfully launched six missions aboard six different launch vehicle configurations from both the East and West Coast launch bases in FY 2018: the Joint Polar Satellite System–1 (JPSS-1) aboard a Delta II 7920 on November 18, 2017, from Vandenberg Air Force Base (VAFB) in California; the Geostationary Operational Environmental Satellite-S (GOES-S) aboard an Atlas V 541 on March 1, 2018, from Cape Canaveral Air Force Station

(CCAFS) in Florida; the Transiting Exoplanet Survey Satellite (TESS) aboard a Falcon 9 on April 18, 2018, from CCAFS in Florida; the Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) aboard an Atlas V 401 on May 5, 2018, from VAFB in California; the Parker Solar Probe (PSP) on August 12, 2018, aboard a Delta IV Heavy from CCAFS in Florida; and the Ice, Cloud, and land Elevation Satellite (ICESat)-2 on September 15, 2018, aboard the final Delta II 7420 from VAFB in California. The LSP also continued to provide launch-related systems engineering, launch integration, and mission design and analysis support to over 60 NASA-sponsored missions in various phases of development. To learn more about these and other NASA science missions, see the Science Mission Directorate (SMD) section in this report.

The LSP continued its efforts to expand the selection of launch vehicles, working across the launch-vehicle industry to support the continued growth of the U.S. commercial space sector by offering competitive opportunities to U.S. commercial launch providers. Currently, launch services task order acquisitions are in work for four science missions: the Geostationary Operational Environmental Satellite (GOES)-T, the Imaging X-ray Polarimetry Explorer (IXPE), Lucy, and the Double Asteroid Redirection Test (DART) missions. 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. To date, CubeSats have been selected from 39 states across the United States, with 70 missions launched and 49 manifested on NASA, National Reconnaissance Office, U.S. Air Force, and commercial missions. In FY 2018, 21 CSLI CubeSats were launched. The Venture Class Launch Services (VCLS) contracts for CubeSats foster a commercial launch market dedicated to flying small-satellite payloads by serving as an alternative to the current rideshare approach, in which one or more CubeSats take advantage of excess payload capacity on a rocket whose primary mission is to launch a larger satellite. Rocket Lab USA has the first VCLS launch scheduled for the end of 2018 aboard the Electron launch

vehicle. Virgin Galactic will follow with a scheduled launch in the first half of 2019 aboard the LauncherOne launch vehicle. In addition, in January 2018, SpaceX successfully completed "Category 2" certification of the Falcon 9 "Full Thrust," which supported the launch of the NASA TESS mission in March 2018. LSP will continue to work toward certifying new commercial launch vehicles to launch high-value payloads. Pre-certification activities are ongoing with Blue Origin's "New Glenn," United Launch Services' "Vulcan," and Northrop Grumman's "Omega" launch vehicles.

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 Commercial Crew Program; SMD's James Webb Space Telescope (Webb), and the NASA–Indian Space Research Organization Synthetic Aperture Radar (NISAR) missions.

Advanced Exploration Systems (AES)

The Advanced Exploration Systems Division pioneers new ways to rapidly develop prototype systems, demonstrate key capabilities, and validate operational concepts to reduce the risk and cost of future human exploration missions. In FY 2018, the AES Division continued the successful execution of 28 research and technology development activities employing about 470 civil servants spread across all NASA Centers. The activities are grouped into four domains: Habitation Systems, Vehicle Systems, Foundational Technologies, and Robotic Precursors.

Activities in the Habitation Systems domain develop systems to enable the crew to live and work safely in deep space, including beyond-Earth-orbit habitats as well as life-support, radiation protection, fire safety, and logistics-reduction systems.

- The Bigelow Expandable Activity Module (BEAM) completed its two-year mission on the ISS in May 2018. NASA and Bigelow Aerospace completed structural analysis to certify that BEAM could be used for the storage of ISS equipment during an extended mission lasting until the retirement of the ISS.

- AES continued the Phase 2 Next Space Technologies for Exploration Partnerships (NextSTEP) contracts with Bigelow Aerospace, Boeing, Lockheed Martin, Orbital ATK, and Sierra Nevada Corporation to develop prototype deep space habitats for ground testing, as well as a contract with Nanoracks to study concepts for converting an expended upper stage into a habitat. These partnerships require the companies to contribute at least 30 percent of their own funding to the efforts. The contractors completed the designs and began assembly of the habitats in preparation for the ground tests that are planned to start in January 2019. The ground tests will assess human factors, subsystem integration, interoperability standards, and common interfaces.
- The Life Support Systems activity launched a second flight of Aerosol Samplers to the ISS and returned samples for laboratory analysis. The Spacecraft Atmosphere Monitor (SAM) Development Unit was assembled and tested in an environmental chamber. SAM will measure trace contaminants in the ISS air. The Critical Design Review for a Brine Processor Assembly (BPA) that will enable recovery of 98 percent of the water from urine was completed. An integrated test of a Plasma Pyrolysis Assembly (PPA), Sabatier reactor, and hydrogen separator was conducted. The PPA recovers hydrogen from the waste methane produced by the Sabatier reactor.
- The Radiation Sensors activity delivered the Hybrid Electronic Radiation Assessor (HERA) flight unit for EM-1 and conducted proof-of-concept experiments to assess the feasibility of using an electrostatic dipole to deflect incoming charged particles for active radiation shielding.
- The Spacecraft Fire Safety activity began the assembly of the Saffire-IV flight experiment that will fly on the Cygnus vehicle. Saffire-IV will investigate the effects of reduced pressure on fire propagation and monitor combustion products and postfire cleanup.
- The Logistics Reduction activity conducted ground integration tests of the Radio Frequency Identification (RFID)–Enabled Autonomous Logistics Management (REALM) system and the Astrobee free flyer. REALM and Astrobee will track ISS inventory and can be used to locate

missing items quickly. This activity also continued the development of the Universal Waste Management System, which is a compact toilet that will be flown on the ISS and Orion. The toilet stall hardware was delivered for launch to the ISS. Two companies (UTAS and Sierra Nevada Corp.) were awarded NextSTEP contracts to develop prototype Trash Compaction and Processing Systems.

Activities in the Vehicle Systems domain develop systems to enable human and robotic exploration vehicles, including advanced in-space propulsion, lander technology, and modular power systems.

- AES is developing high-power electric thrusters for the next generation of solar electric propulsion systems via three NextSTEP Advanced Propulsion activities. Ad Astra Rocket Company is developing the Variable Specific Impulse Magnetoplasma Rocket (VASIMR); Aerojet Rocketdyne is developing a nested Hall thruster; and MSNW is developing an Electrodeless Lorentz Force plasma thruster. In the final year of their three-year contracts, the companies assembled their thrusters, upgraded their test facilities, and began short-duration tests. The goal is to test the 100-kilowatt thrusters in a vacuum chamber for 100 continuous hours. The MSNW contract was de-scoped because they could not meet thruster performance targets.
- The Lander Technology activity assembled a brassboard system to demonstrate liquefaction of cryogenic propellants produced by in situ resource utilization. The Lunar Cargo Transportation and Landing by Soft Touchdown (Lunar CATALYST) initiative continued to provide engineering and test support for three companies developing robotic lunar landers: Astrobotic, Moon Express, and Masten Space Systems.
- NASA issued a Request for Proposals for Commercial Lunar Payload Services (CLPS). CLPS will be used to procure end-to-end commercial launch and landing services for transporting small payloads to the surface of the Moon.
- The mockup Crew Module (CM) for the Orion Ascent Abort flight test vehicle completed acoustics testing, and the CM was mated with the Separation Ring. A mockup of the Orion capsule and an active Launch

Abort System will be launched on a booster rocket in May 2019 to demonstrate boost phase abort capabilities.

Activities in the Foundational Technologies domain enable more-efficient mission and ground operations and those that allow for more Earth independence, including autonomous mission operations, avionics and software, in situ resource utilization, in-space manufacturing, synthetic biology, and communication technologies.

- The Avionics and Software activity conducted an integrated test of a reference avionics architecture that uses three voting computers and time-triggered Ethernet to control life support, power, communications, and other subsystems for a deep space habitat.
- The In-Space Manufacturing activity awarded contracts to three companies (Interlog, Techshot, and Tethers Unlimited) to develop a prototype Multi-Material Fabrication Lab for demonstration on the ISS. This activity also delivered the Refabricator payload, which will recycle plastic parts on the ISS and produce feedstock for an integral 3D printer.
- The In-Situ Resource Utilization (ISRU) activity selected ten contracts via a NextSTEP Broad Agency Announcement to conduct ISRU system studies and develop critical components and subsystems for the acquisition and processing of extraterrestrial resources to produce water, oxygen, and methane fuel.
- The Disruption Tolerant Networking (DTN) activity conducted interoperability tests with the Korea Aerospace Research Institute (KARI) in preparation for their Korea Pathfinder Lunar Orbiter mission and demonstrated DTN on the 21-meter antenna at Morehead State University for communicating with CubeSats.

Activities in the Robotic Precursor domain develop robotic missions and payloads to acquire strategic knowledge on potential destinations for human exploration to inform systems development, including CubeSats launched on EM-1, technology demonstrations on the Mars 2020 mission, and instrument development.

- AES continued the development of three payloads for the Mars 2020 mission. The Engineering Model for the Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE) was assembled and tested. NASA

provided a sky camera for the Mars Environmental Dynamics Analyzer (MEDA) that is being developed by Spain. The Mars Entry, Descent, and Landing Instrumentation–2 (MEDLI-2) payload completed its Critical Design Review. MOXIE will demonstrate the production of oxygen from the Mars atmosphere; MEDA is a surface weather station; and MEDLI-2 is a suite of temperature and pressure sensors on the Mars 2020 heat shield to validate aerothermal models.

- AES plans to launch five CubeSats on EM-1 to fill gaps in our knowledge about space environments and the availability of lunar resources. These activities completed their design and safety reviews and began spacecraft integration. BioSentinel will investigate the effects of deep space radiation on yeast DNA. Lunar Flashlight will search for ice from lunar orbit using lasers to illuminate permanently shadowed lunar craters. Near-Earth Asteroid Scout will use a solar sail to fly by an asteroid. The Lunar Infrared (LunIR) CubeSat is a NextSTEP partnership with Lockheed Martin to fly by the Moon and test a new infrared sensor. Lunar IceCube is a NextSTEP partnership with Morehead State University to detect water and other volatiles from lunar orbit using a broadband infrared spectrometer.
- AES selected Arizona State University to develop the ShadowCam instrument for flight on the Korea Pathfinder Lunar Orbiter. ShadowCam will image ice in permanently shadowed lunar craters. The instrument Preliminary Design Review was completed.

The AES Division is leading the definition of system concepts, requirements, and design standards for the Gateway concept that will be launched into lunar orbit around 2023. The Gateway may consist of a habitat, a solar electric propulsion and power element, logistics capabilities, and an airlock/docking node. Orion will dock with the Gateway, and a crew will stay onboard to gain experience in living and working in deep space and to test critical life-support and logistics management technologies for long missions.

Two design and analysis cycles were completed to refine the Gateway configuration and concept of operations. A Formulation Synch Review was held to coordinate activities supporting Gateway formulation, including allocating

functions to the Gateway elements, defining system requirements and interoperability standards, developing an integrated master schedule, and establishing an acquisition strategy.

NASA initiated the development of the Power and Propulsion Element (PPE), which is the first element of the Gateway ready to be launched in 2022. The PPE consists of a commercial spacecraft bus and a high-powered Solar Electric Propulsion (SEP) system. A solicitation was issued for PPE development and flight demonstration. Contract awards are targeted for March 2019.

Power Propulsion Element

In FY 2018, NASA made substantial progress toward the development of the PPE planned as the first element of the Gateway. The PPE will utilize advanced 50-kilowatt-class SEP to provide relocation capabilities for the Gateway as well as orbit maintenance, electrical power, communications, and research payload accommodations. In November 2017, NASA competitively awarded five contracts to U.S. industry to study PPE concepts and address key questions. These studies, conducted by Boeing, Lockheed Martin, Orbital ATK, Sierra Nevada Corporation, and Space Systems Loral, helped inform a PPE acquisition approach that leverages existing industry capability and plans for a high-powered SEP. Final study briefings were completed on March 23, 2018.

During FY 2018, the process of PPE requirements definition was conducted in coordination with the Gateway and in interactions with potential International Partners. A study of a potential International Partner–provided payload to be hosted on the PPE was completed, including inputs from the five PPE study contractors. The PPE, the Gateway, and a potential International Partner have also held discussions to address interfaces and operations concepts between the PPE and the possible next Gateway element, which could be docked to the PPE. NASA requirements for the PPE were set, supporting the PPE acquisition.

On November 30, 2017, NASA issued a sources-sought notice for a PPE. A synopsis was published on February 20, 2018. A draft Broad Agency Announcement (BAA) for Spaceflight Demonstration of a PPE was released on June 21, 2018, for industry comment. An industry day was held at Glenn Research Center on

July 10, 2018. Many of the industry participants expressed their appreciation for a high-quality draft BAA and a very productive and useful industry day event. Industry comments were submitted by July 20, 2018. The final BAA was posted on September 6, 2018. Through this solicitation, NASA is seeking one or more partnerships with industry for the development and spaceflight demonstration of a PPE. At the completion of the demonstration, the BAA includes the option for NASA to acquire the PPE for NASA's use as the first element of the Gateway.

Space Communications and Navigation

NASA's Space Communications and Navigation (SCaN) Program continued to provide programmatic oversight and management of the Agency's space communications and tracking capabilities and served as the Agency's representative in domestic and international fora 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 and deep space and commercial space enterprises.

NASA's 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)—continued their long record of providing their services at an average proficiency level of 99 percent or better, well 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 2018, SCaN networks provided communication and navigation (C&N) services to 71 missions, including

human spaceflight C&N requirements of the International Space Station. 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.

With the completion of an Independent Review Team study of the progress made in the SN Ground Sustainment System (SGSS) project and approval to proceed, SCaN continued the construction of this major ground system upgrade activity, completing the factory Systems Acceptance Test at the end of FY 2018. 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 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. 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. During FY 2018, NASA supported the IOAG's efforts to develop an interoperable lunar communications and navigation architecture, including standards which were internationally approved by the ISS Program as the set of communications and navigation standards for the Lunar Gateway Program. NASA contributed to the IOAG's preparations for an Interoperability Plenary of the IOAG member

agencies' senior leadership; the plenary provides strategic oversight and guidance for the IOAG.

In FY 2018, SCaN continued building two Optical Ground Stations (OGSes)—OGS-1 at the Jet Propulsion Laboratory in California and OGS-2 in Hawaii, the U.S. locations with the least interfering cloud coverage. Through participation in the IOAG and the CCSDS, NASA reached agreements with JAXA and Centre National d'Études Spatiales (CNES) on optical communications standards, making interoperability between the participating agencies possible.

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 State Department–led U.S. delegation, SCaN continued coordination on agenda items on spectrum issues of interest and concern to NASA that will be addressed at the World Radiocommunication Conference 2019.

SCaN continued sponsoring the National Space-Based Positioning, Navigation, and Timing (PNT) Advisory Board, an independent Federal Advisory Committee Act (FACA) board, and, as Executive Director, coordinated its biannual sessions and an additional intersession meeting. Key FY 2018 deliverables to the National Space-Based PNT Executive Committee, chaired by the Deputy Directors of Defense and Transportation, include a recommendation on Global Positioning System (GPS) spectrum protection as well as a Topics Paper describing the benefits of GPS across areas of the U.S. economy and with recommendations to preserve them. NASA also assisted the Air Force in the procurement process for GPS-IIIF to protect capabilities available to users within the Space Service Volume (SSV), which covers altitudes above LEO and up to Geosynchronous Earth Orbit (GEO) altitude. NASA has also continued working with foreign Global Navigation Satellite Systems (GNSS) service providers to develop an Interoperable Multi-GNSS SSV that expands the PNT capabilities available to space users well beyond what any one GNSS can provide on its own. A key FY 2018 deliverable is the United Nations' "The Interoperable Global Navigation Satellite Systems Space Service Volume" booklet developed through cooperation at the International Committee on GNSS (ICG), now available in printed form at the United Nations

Headquarters in New York and online. This is a new international baseline for mission planners of partner space agencies and commercial space to use GPS/GNSS for cis-lunar operations. Finally, the NASA Search and Rescue (SAR) program continues to implement the GPS Search and Rescue (GPS SAR), the U.S. contribution to the GNSS-based Medium Earth Orbit Search and Rescue (MEOSAR) to locate emergency beacons. Key events included qualifying the emergency location beacon for the Orion crew life-preserver units and successfully tracking the October 11, 2018, Soyuz launch abort and emergency landing with only 1.7 kilometers (a little over one mile) in location error.

Science Mission Directorate

NASA's Science Mission Directorate (SMD) seeks new knowledge and understanding of our planet Earth, our Sun and solar system, and the universe. Working with the scientific community, industry, and other partners, SMD develops the world's leading space observatories, as well as air-based and ground-based platforms, to provide unique data and imagery, enabling scientists to conduct scientific studies and advance the frontiers of discovery. In FY 2018, SMD operated more than 100 space missions and sounding rocket, balloon, and Earth-based investigations. Altogether, SMD worked with more than 10,000 U.S. scientists.

SMD organizes its work into four broad scientific pursuits: Earth Science, Planetary Science, Heliophysics, and Astrophysics. Science is an interconnected enterprise, and within SMD, discoveries and capabilities in one scientific discipline help to inform and enable those in the others. SMD's science activities follow three core elements: First, SMD is discovering the secrets of the universe through studies of the Sun and its effect on the solar system, Earth, other planets and solar system bodies, and the universe. These fundamental scientific discoveries enhance our understanding of the nature of the universe, shed light on some of most pressing and existential questions facing humankind, and help us to prepare for human and robotic exploration further into the solar system and beyond. Second, SMD searches for life elsewhere through research on the habitability of locations in the solar system, such as Mars and Europa, as well as through studies of the thousands of potentially habitable worlds around other stars. Finally, SMD is safeguarding and

improving life on Earth by detecting and studying near-Earth asteroids and comets, investigating the cause and effects of severe space weather events, and developing applications for use in improving life on Earth—efforts ranging from natural disaster response and recovery to applications for agriculture and transportation.

SMD also takes an integrated approach to technology development and science activation. SMD makes targeted technology investments that enable NASA to build the challenging and complex missions that accomplish its groundbreaking science. In FY 2018, SMD continued to make important investments in small spacecraft platforms that offer the potential to reduce the cost or broaden capabilities for scientific discovery through faster development times and innovative mission architectures, including constellations of small satellites. Investments are also helping to develop new optical systems that could contribute to the search for exoplanets around stars other than our Sun; a heatshield that would enable missions to withstand the intense atmospheric heating on Venus, Saturn, and Uranus; and many other technologies.

SMD's Science Activation program leverages unique NASA infrastructure and scientific experts to engage with learners of all ages. In FY 2018, the Science Activation program continued its work through 25 cooperative agreements leveraging over 200 partners. SMD's activities reach a broad audience, enabling STEM education and improving scientific literacy in the United States by working with community-based institutions, including libraries, museums, science centers, and planetariums, as well as digital and online platforms.

Earth Science

Earth is a complex, dynamic system that we do not yet fully understand. The Earth Science Division (ESD) studies Earth's land, atmosphere, and oceans and the connections between them across spatial and temporal scales to advance knowledge of Earth as a system, to meet the challenges of environmental change, and to improve life on our planet. ESD develops and operates a coordinated series of satellite and Earth-based missions for long-term global observations. It also sponsors research that answers fundamental science questions and supports efforts to develop applications that leverage NASA observations to provide practical benefits

for society in a wide range of areas, including weather, natural disasters, climate, oceans and water management, and agricultural production. The program invests in innovative new technologies and works closely with global partners in government, industry, and the public.

NASA launched a number of important new Earth Science missions in FY 2018. The joint U.S.-German Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) mission launched in May 2018; it succeeded the highly successful GRACE mission, which ended just seven months earlier, in October 2017, after 15 years in orbit. Like its predecessor, GRACE-FO consists of twin satellites that operate in tandem to provide unique measurements of Earth's gravitational pull. These measurements reveal the movement of mass around Earth, which can be used to understand changes in global groundwater resources, identify the location of dry soils that can contribute to drought, and measure the amount of ice being lost from the Greenland and Antarctic ice sheets.

On September 15, 2018, NASA launched the Ice, Cloud and land Elevation Satellite–2 (ICESat-2) mission. The mission measures elevation to see how much glaciers, sea ice, and ice sheets are rising or falling and will help to narrow the range of uncertainty in forecasts of future sea level rise. It also measures the height of ocean and land surfaces, contributing to flood and drought forecasts, wildfire response, and maritime navigation. ICESat-2 represents a significant advancement over its predecessor, carrying the most advanced laser instrument of its kind. ICESat-2's laser will fire 10,000 times in one second, compared to a rate of 40 firings per second on the original ICESat. This higher rate will result in more detail in the measurements of height around Earth—ICESat-2 is able to measure the average annual change in vast ice sheets down to the width of a pencil.

After its launch onboard NOAA's Joint Polar Satellite System–1 (JPSS-1) satellite in November 2017, the Clouds and the Earth's Radiant Energy System Flight Model 6 (CERES FM6) became the sixth in a family of instruments dating back to the 1990s to monitor Earth's energy budget—the balance between the solar radiation arriving at Earth from the Sun and the reflected solar radiation and thermal emissions leaving Earth. Earth's radiation budget provides a key measurement in understanding the warming of Earth—if you have more energy coming in than going out, the system will heat up.

The Total and Spectral solar Irradiance Sensor (TSIS-1), launched in December 2017 and installed on the International Space Station two weeks later, became fully operational, with all instruments collecting science data, by March 2018. TSIS measures the total amount of light energy emitted by the Sun and measures how the Sun's energy is distributed over the ultraviolet, visible, and infrared regions of light. The instrument helps to better understand the Sun's influence on Earth's radiation budget, ozone layer, atmospheric circulation, and ecosystems and provides insight into the effects that solar variability has on the Earth system and climate change. TSIS continues 40 years of measurements of energy emitted by the Sun—measurements that can only be taken from the vantage point of space.

In addition to these space-based missions, SMD engaged in airborne studies of Earth. Operation IceBridge, an aircraft campaign designed to bridge the gap between the ICESat-1 and ICESat-2 missions, continued to carry out flights in the Arctic and Antarctic. Several flights included collaborations with international missions, such as underflights of the European Space Agency (ESA) Sentinel-3A and CryoSat-2 satellites over sea ice, or overflights of the U.S. Navy's 2018 Ice Exercise (ICEX) campaign exploring sea ice north of Alaska.

In partnership with the National Science Foundation (NSF), NASA embarked on the Export Processes in the Ocean from Remote Sensing (EXPORTS) oceanographic campaign. EXPORTS is the first coordinated multidisciplinary science campaign of its kind to study the life and death of the small organisms—microscopic plankton—that play a critical role in removing carbon dioxide from the atmosphere and in the ocean's carbon cycle.

In April 2018, NASA's North Atlantic Aerosols and Marine Ecosystems Study (NAAMES) mission began its fourth and final deployment, making it the first research mission to conduct an integrated study of all four distinct phases of the world's largest phytoplankton bloom in the North Atlantic and how they impact the atmosphere. NAAMES makes use of both measurements taken aboard ships and aircraft to investigate the links between the oceans, atmospheric particles, and clouds.

In 2018, NASA flew the last deployment of the Atmospheric Tomography (ATom) mission. ATom used advanced instruments aboard a DC-8 research aircraft to sample over 400 different gases and a broad range of airborne particles, improving our understanding of how gases and pollutants travel around the globe.

In addition to adding new missions, NASA has been taking full advantage of the missions already operating. Imagery from Landsat 8 and the Aqua satellite showed summer phytoplankton and cyanobacteria blooms in the Baltic and Barents Seas. These images can help to identify the location and size of potential "dead zones"—areas where these tiny organisms consume nutrients in the water and grow at a rate that depletes the oxygen content of the water, harming fish and other marine life.

Satellites contribute to our understanding of the atmosphere, as well as the ocean. A study of air pollution over China that used data from NASA's CERES instrument showed that the smog not only makes it harder to breathe but also reduces the amount of sunlight reaching China's solar panels. Other studies, based on satellite and ground-based sensors monitoring air pollution in China, showed that while levels of air pollution in China continue to be among the highest in the world, key pollutants have been decreasing in recent years. Scientists also found that India's emissions are on the rise—at least in the case of sulfur dioxide. This finding was based on inventories of the number of factories, power plants, and other contributors to sulfur dioxide, as well as data from the Ozone Monitoring Instrument (OMI) on NASA's Aura satellite.

The NASA Earth Science Disasters Program mobilizes NASA resources to assist with the detection of, response to, and/or recovery from wildfires, earthquakes, floods, severe weather, and other disasters. NASA instruments are often the first to detect actively burning fires in remote areas. They can help to track the transport of smoke from fires, provide information for fire management, and map the extent of changes to ecosystems, based on the extent and severity of burn scars. In 2018, California experienced its largest fire in recorded history—the Thomas Fire, which burned for more than six months. Satellites, including the National Oceanic and Atmospheric Administration (NOAA)–NASA Suomi National Polar Partnership (NPP) satellite and NOAA's JPSS-1 satellite, known as NOAA-20 now that it is in orbit and operational, were used to monitor the extent of the flames, hot spots, and smoke.

NASA's ability to monitor flooding received a boost in 2018 as scientists evaluated the first year of data from the Cyclone Global Navigation Satellite System (CYGNSS) mission. Researchers found that GPS reflection data over land, a measurement used by CYGNSS, are very sensitive to the amount of water either in the

soil or on the surface, making that type of measurement useful for the creation of flood maps.

NASA is also applying its technology and expertise in another life-saving application: prevention of disease outbreaks. In August, measurements from NASA Earth-observing research satellites were used to help combat a potential outbreak of life-threatening cholera. Humanitarian teams in Yemen targeted interventions in areas identified by a NASA-supported project that precisely forecasts high-risk regions based on environmental conditions observed from space. The forecast tool analyzes a variety of NASA satellite observations, including precipitation data from the Global Precipitation Measurement mission, air and ocean temperatures from the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments on NASA's Terra and Aqua satellites, and measurements of phytoplankton concentrations in nearby coastal ocean areas.

Through technology development, research, and development of new applications, NASA's Earth Science program enhances our fundamental understanding of our home planet and improves everyday life on Earth. Below are five research highlights from FY 2018.

NASA Soil Moisture Data Advances Global Crop Forecasts

Data from the first NASA satellite mission dedicated to measuring the water content of soils are now being used operationally by the U.S. Department of Agriculture to monitor global croplands and make commodity forecasts. The Soil Moisture Active Passive mission, or SMAP, launched in 2015 and has helped map the amount of water in soils worldwide. Direct measurements of soil moisture available from SMAP replaced estimates of this critical variable based on precipitation and temperature, increasing accuracy.

NASA Satellites Reveal Major Shifts in Global Freshwater

In the first study of its kind, scientists combined data from multiple NASA satellites with data on human activities to map locations where freshwater is changing around the globe and determine why. The study, published in May 2018 in the journal *Nature*, finds that Earth's wetland areas are getting wetter and dry areas are getting drier due to a variety of factors, including human water management,

climate change, and natural cycles. The study relied on data from the Gravity Recovery and Climate Experiment (GRACE), the Global Precipitation Measurement (GPM) mission, and the NASA–U.S. Geological Survey (USGS) Landsat mission.

Pollutant Emissions Leveling Off a Bit in the U.S.

A study by NASA-supported researchers showed that while air quality in the United States has improved since the 1960s, it has not improved as quickly as predicted by models. Data from the OMI instrument on NASA's Aura satellite and the Measurement of Pollution in the Troposphere (MOPITT) instrument on NASA's Terra satellite were used to provide global, standardized views of emissions, not subject to differences in regional and national ground-reporting. These measurements showed that decreases in carbon monoxide and nitrogen oxide—chemicals emitted by vehicles and industrial sources—have leveled off in recent years.

Global Study of World's Beaches Shows Threat to Protected Areas

A study of the world's sandy shorelines with satellite data found that they have increased slightly on a global scale over the past three decades but decreased in protected marine areas, where many beaches are eroding. Researchers used machine learning techniques to analyze data from the NASA-USGS Landsat mission, resulting in a study of annual shorelines between 1984 and 2016 for the entire world. Differences in beach erosion seem to be largely influenced by human interventions along the coast.

NASA Study: First Direct Proof of Ozone Hole Recovery Due to Chemicals Ban

Scientists were able to use direct satellite observations of the ozone hole to show that levels of ozone-destroying chlorine are declining, reducing ozone depletion. The decline in chlorine is due to the international ban on chlorine-containing humanmade chemicals called chlorofluorocarbons (CFCs). Past studies have used statistical analyses of changes in the ozone hole's size to argue that ozone depletion is decreasing. This study is the first to use measurements of the chemical composition inside the ozone hole to confirm that not only is ozone depletion decreasing, but that the decrease is caused by the decline in CFCs.

Joint Agency Satellite Division

In addition to its own Earth observation satellites, NASA also develops and launches instruments and satellites on behalf of NOAA on a reimbursable basis through the Joint Agency Satellite Division (JASD). NASA launched NOAA's JPSS-1 and Geostationary Operational Environmental Satellite 17 (GOES-17) in November 2017 and March 2018, respectively. Descriptions of these satellite programs can be found in the Department of Commerce chapter of this report.

Heliophysics

NASA's Heliophysics Division (HPD) aims to understand the Sun and its interactions with Earth and the solar system, including space weather. The Heliophysics Division operates a variety of missions between Earth and the Sun that collect data to provide insight into these studies. It supports research to advance our fundamental understanding of the Sun and its impact on our solar system and to improve our ability to understand and forecast the impacts of space weather events on people and systems on Earth.

In August 2018, HPD launched the Parker Solar Probe, a spacecraft the size of a small car that will fly closer to the Sun than any previous mission. When it makes its first pass close to the Sun in November 2018, Parker will fly through the solar atmosphere—the corona—and help to solve foundational mysteries of the Sun. It will investigate the drivers of supersonic solar wind, which blows a steady stream of solar material through the entire solar system, and help scientists to understand why the corona is more than 300 times hotter than the Sun's surface.

Earlier in the year, NASA launched the Global-scale Observations of the Limb and Disk (GOLD) mission, the first NASA mission to fly as a hosted payload aboard a commercial satellite. GOLD will study the little-understood region where Earth's uppermost atmosphere meets space—a critical boundary layer that responds both to terrestrial weather below and space weather above. GOLD is expected to be joined by NASA's Ionospheric Connection Explorer (ICON), which will study the ionosphere and neutral upper atmosphere. ICON will fly just 350 miles above Earth, where it can gather close-up images of this region. Together, GOLD and ICON will provide the most comprehensive ionosphere

observations gathered to date, enabling a deeper understanding of how our planet interacts with space.

HPD also utilizes sounding rockets to advance science. In October 2017, HPD launched the Focusing Optics X-ray Solar Imager (FOXSI). The sounding rocket flight allowed for just six minutes of data collection, but within that time, the cutting-edge instrument found the best evidence to date of a phenomenon scientists have been seeking for years: signatures of tiny solar flares that could help explain the mysterious extreme heating of the Sun's outer atmosphere. A second version of FOXSI, launched in September 2018, is further investigating this issue by taking more precise measurements that will provide a more complete picture of nanoflares and their contribution to coronal heating.

In FY 2018, NASA selected a team to implement the Interstellar Mapping and Acceleration Probe (IMAP) mission, the highest priority in the National Academy of Sciences (NAS) Heliophysics Decadal Survey, and are partnering with NOAA to use a single launch vehicle for IMAP and a NOAA space weather monitoring payload. The IMAP mission will help researchers better understand the boundary of the heliosphere, a sort of magnetic bubble surrounding and protecting our solar system.

The Geospace Dynamics Constellation (GDC) mission, which was in a definition phase in FY 2018, will provide key understanding of the interaction of various regions in geospace where space weather has its greatest impact on space assets. GDC, together with the proposed Explorer missions, will investigate fundamental space physics energization and coupling phenomena in the Sun's extended atmosphere and in Earth's magnetosphere and will develop observation techniques directly applicable to space weather capabilities.

A number of missions continued to collect data throughout FY 2018, advancing our understanding of heliophysics. NASA's Magnetospheric Multiscale (MMS) mission consists of four satellites flying in formation at speeds of up to 22,300 miles per hour. The first phase of the mission involved the study of the magnetosphere—the magnetic bubble surrounding Earth—on the side of the planet closest to the Sun. Phase two of the mission was an exploration of the magnetosphere on the dark side of Earth. In January 2018, MMS began a new extended mission phase, returning to the dayside but flying at a distance about twice as far from Earth as in

phase one. MMS data has already been used in 340 papers by scientists around the world, and this extended phase will open doors to even more discoveries.

A study published in March 2018 used data from the Interstellar Boundary Explorer (IBEX) spacecraft to better understand what happens when solar wind suddenly begins to blow significantly harder. Researchers found that two years after the solar wind pressure—a combined measure of its speed and density—had increased by approximately 50 percent, it significantly expanded the size of the heliosphere, the bubble of solar wind that encases all of the planets in our solar system and much of the space beyond them, separating the domain of our Sun from that of interstellar space.

Scientists used NASA's Solar and Terrestrial Relations Observatory-A, or STEREO–A, spacecraft, which circles the Sun between Earth and Venus, to take longer, more frequent exposures of the solar corona than had been taken in the past. After using unique processing methods, they were able to show in a publication released in July 2018 that the corona is structured, not smooth and homogenous, as previously thought. This structure may help to explain the variability seen in the solar wind when it hits Earth's magnetosphere.

Some studies make use of more than one Heliophysics mission to enable their research. In a paper published in February 2018, scientists used data from both the Solar and Heliospheric Observatory (SOHO) and the STEREO-A and -B satellites to study two Coronal Mass Ejection (CME) events—explosions of plasma erupting from the Sun. Using data from multiple spacecraft allowed scientists to develop a 3D view of the events, reconstructing their journey from space. This work helped scientists to deduce important pieces of information for space weather forecasting—in this case, for the first time, the density of the plasma around the shock, in addition to the speed and strength of the energized particles. All of these factors are key to assessing the danger CMEs present to astronauts and spacecraft.

In another study, scientists combined data from 16 separate NASA and Los Alamos National Laboratory spacecraft to understand how a particle phenomenon in the magnetic environment around Earth occurs. Data from each individual mission are only able to provide a snapshot of what the environment looks like at a specific place and a specific time. While this snapshot allows scientists to understand some space plasma phenomena in detail, it is difficult to get a comprehensive

picture of where the particles came from and where they are going. However, by combining datasets from spacecraft situated in locations spread around Earth, researchers were able to address big-picture questions about particle movement.

The Heliophysics Division collects data and supports technology development and research that improve our understanding of the Sun and its effects on Earth and other planets in our solar system. Below are five research highlights from FY 2018.

NASA Spacecraft Discovers New Magnetic Process in Turbulent Space

Scientists working with MMS uncovered a new type of magnetic event in the near-Earth environment by using an innovative technique to squeeze extra information out of the data. Scientists discovered that magnetic reconnection—which occurs when crossed magnetic field lines snap, explosively flinging away nearby particles at high speeds—occurs not only in relatively calm areas, as originally thought, but also in turbulent zones. This discovery could help scientists better understand this important phenomenon and potentially improve forecasts of space weather events in the future.

NASA's Solar Dynamics Observatory Reveals How a Magnetic Cage on the Sun Stopped Solar Eruption

Using data from NASA's Solar Dynamics Observatory (SDO), researchers provided insight into why some strong solar flares—intense bursts of radiation and light—are followed by a CME—a massive, bubble-shaped eruption of solar material and magnetic field—while others are not. SDO data regarding the magnetic fields at the Sun's surface showed that in the area where a large solar flare had occurred in 2014, a twisted magnetic "rope"—known to be associated with the onset of CMEs—had formed, but it had been covered by a dense "cage" of magnetic fields. The scientists found that this magnetic cage physically prevented a CME from erupting that day.

Mystery of Purple Lights in Sky Solved with Help from Citizen Scientists

In March 2018, scientists published a study providing insight into a phenomenon with help from citizen scientists. The phenomenon, referred to as the Strong Thermal Emission Velocity Enhancement (STEVE), did not look like a normal

aurora. Rather than being oval-shaped and green, blue, or red, STEVE was a purple line. Using data contributed by citizen scientists, as well as data collected by observing systems on the ground and in space, researchers demonstrated that, like aurora, STEVE was caused by charged particles from the Sun interacting with Earth's magnetic field lines. However, these field lines were closer to Earth's equator, and the particles were fast-moving and extremely hot.

Pulsating Aurora Mysteries Uncovered with Help from NASA's Time History of Events and Macroscale Interactions during Substorms Mission

Auroras typically appear as shimmering green, blue, or red areas in the sky, but another type of aurora, called a pulsating aurora, appears less frequently and produces a dimmer display. Scientists using data from NASA's Time History of Events and Macroscale Interactions during Substorms (THEMIS) mission and Japan's Exploration of energization and Radiation in Geospace (ERG), also known as Arase, satellite found that pulsating auroras are caused by a particular type of plasma wave, called a whistler mode chorus. This wave hits the magnetosphere, scattering electrons down to Earth's atmosphere, causing the aurora. The results also help scientists better understand how plasma waves can influence electrons—something that occurs in processes across the universe.

Predicting the Corona's Appearance During the August 21, 2017, Total Solar Eclipse

Researchers used data from the Solar Dynamics Observatory to develop a model that simulates the Sun's corona. They used measurements of magnetic fields on the Sun's surface to predict the structure of the magnetic field that shapes the corona. The eclipse offered the scientific community a unique opportunity to test the model because the coronal region near the Sun can be examined in more detail during an eclipse than at any other time. Researchers found that the structure of the magnetic field during the 2017 total solar eclipse predicted by the model bore a striking resemblance to the actual corona observed at that time. The results from this model can help to provide context for the Parker Solar Probe mission as it travels through the corona later in 2018.

Planetary Science

NASA's Planetary Science Division (PSD) aims to ascertain the content, origin, and evolution of the solar system and the potential for life elsewhere. PSD develops spacecraft that travel to other objects within our solar system, conducting flybys, orbiting around or landing on these objects, and sometimes returning samples to Earth. PSD develops innovative new technologies to enable spacecraft to travel to locations ranging from the innermost planet, Mercury, to the edges of the solar system, and it supports research to enhance our understanding of our solar system. PSD also supports efforts to identify, characterize, and develop responses to potentially hazardous near-Earth objects (NEOs).

In December 2017, President Trump released Space Policy Directive 1, a change in national space policy that provides for a U.S.-led, integrated program with private-sector partners for a human return to the Moon, followed by missions to Mars and beyond. In alignment with the plan, NASA is preparing to conduct more research on the Moon's surface ahead of a human return and intends to purchase new small lunar payload delivery services. In September 2018, NASA released a Request for Proposals encouraging the U.S. commercial space industry to introduce new technologies to deliver payloads to the Moon. This request for Commercial Lunar Payload Services (CLPS) will further expand efforts to support development and partnership opportunities on the lunar surface.

Long-term exploration and development of the Moon will give us the experience for the next giant leap—human missions to Mars and destinations beyond. NASA's Science Mission Directorate continues to make important progress in our studies of the Red Planet. In May 2018, NASA launched the Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) lander. Insight is scheduled to land on Mars in November 2018 and study for the first time what lies deep beneath the surface of the planet. The InSight lander will probe and collect data on Martian earthquakes, heat flow from the planet's interior, and the way the planet wobbles to help scientists understand what makes Mars tick and the processes that shaped the four rocky planets of our inner solar system.

Launched along with InSight were two CubeSats, called Mars Cube One A (MarCO-A) and MarCO-B. They are designed to trail InSight on the way to Mars,

aiming to relay data about InSight as it enters the planet's atmosphere and attempts to land. The MarCO mission is a test of miniaturized communication and navigation technology that can blaze a path for future CubeSats sent to other planets.

When InSight arrives at Mars, it will join numerous NASA missions already there. In March 2018, Mars Curiosity celebrated its 2,000th Martian day, or sol, on the Red Planet. In June, the rover analyzed drilled samples in one of its onboard labs for the first time in more than a year, using a technique designed by NASA engineers to overcome a mechanical issue that took the drill offline in December 2016. Elsewhere on Mars, NASA's Opportunity rover went silent in June 2018 when a planet-encircling dust storm cut off solar power for the nearly 15-year-old rover. Scientists will not know the status of the rover until the skies clear and the rover recharges enough to attempt to "phone home." At the time of writing, the dust storm has largely dissipated, however, Opportunity still has not responded.

In the meantime, NASA's Mars Reconnaissance Orbiter (MRO) used two instruments to study the dust storm. Each day, the Mars Color Imager (MARCI) mapped the entire planet in midafternoon to track the evolution of the storm. Meanwhile, MRO's Mars Climate Sounder (MCS) instrument measured how the atmosphere's temperature changes with altitude. NASA's Mars Atmosphere and Volatile Evolution mission (MAVEN) continues to examine how the dust storm affects Mars's upper atmosphere.

NASA has also continued to develop the next round of scientific Mars missions, announcing in May 2018 that the Mars 2020 mission will include the Mars Helicopter, a small, autonomous rotorcraft, to demonstrate the viability and potential of heavier-than-air vehicles on the Red Planet. As a technology demonstration, the Mars Helicopter is considered a high-risk, high-reward project. If it does not work, the Mars 2020 mission will not be impacted. If it does work, helicopters may have a real future as low-flying scouts and aerial vehicles to access locations not reachable by ground travel.

In July, NASA's Juno mission marked two years of studying Jupiter and its moons, continuing to enable a wide array of research findings. Juno collected data on a new heat source close to the south pole of the moon Io that could indicate a previously undiscovered volcano. The mission continued to monitor Jupiter's Great Red Spot, showing that the iconic feature penetrates well below the clouds. The spot

has been shrinking for a century and a half, and scientists found that the storm seems to be growing taller as it gets smaller in diameter.

NASA's Dawn spacecraft entered its lowest-ever orbit in June 2018 for a close-up examination of the inner solar system's only dwarf planet—less than 30 miles above the surface of Ceres. Besides the high-resolution images, the spacecraft is collecting gamma-ray and neutron spectra, infrared and visible spectra, and gravity data. The main goal of the observations is understanding the evolution of Ceres and testing for possible ongoing geology.

After an almost-two-year journey, NASA's asteroid sampling spacecraft, the Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer (OSIRIS-REx), caught its first glimpse of asteroid Bennu in August 2018 and began the final approach toward its target. New images are being released as they are available. OSIRIS-REx is NASA's first mission designed to visit a near-Earth asteroid, survey the surface, collect a sample, and deliver it back to Earth. The spacecraft has traveled approximately 1.1 billion miles (1.8 billion kilometers) since its September 2016 launch and is scheduled to arrive at Bennu in December 2018.

OSIRIS-REx is NASA's first asteroid sample return mission; however, the Agency has been observing these and other near-Earth objects (NEOs) for more than 20 years. NEOs are asteroids and comets in orbits that bring them into the inner solar system, within 121 million miles (195 million kilometers) of the Sun, and also within roughly 30 million miles (50 million kilometers) of Earth's orbit around the Sun. There are now over 18,000 known NEOs, and the discovery rate averages about 40 per week. No known asteroid poses a significant risk of impact with Earth over the next 100 years; however, researchers continue to study and characterize these objects and assess the danger they may pose in the future. In June 2018, the U.S. Federal Government released the "The National Near-Earth Object Preparedness Strategy and Action Plan," which organizes efforts related to NEOs within the Federal Government over the next 10 years to ensure that the Nation can more effectively respond should circumstances warrant.

NASA's Planetary Science Division uses an array of spacecraft to help us understand our solar system and the potential for life elsewhere and undertakes efforts to understand and prepare for potentially hazardous NEOs. Below are five research highlights from FY 2018.

Ice Confirmed at the Moon's Poles

In a study published in August 2018, a team of scientists used data from NASA's Moon Mineralogy Mapper (M3) instrument to identify three specific signatures that definitively prove that there is water ice at the surface of the Moon. M3 was launched aboard the Chandrayaan-1 spacecraft by the Indian Space Research Organization in 2008. Not only did it collect data that picked up the reflective properties we would expect from ice, but M3 also was able to directly measure the distinctive way the ice molecules absorb infrared light so that it could differentiate between liquid water, vapor, and solid ice.

NASA Finds Ancient Organic Material, Mysterious Methane on Mars

NASA's Curiosity rover found organic molecules—preserved in rocks on Mars—that suggest that the planet could have supported ancient life. Curiosity also found seasonal variations in the levels of methane in the Martian atmosphere that could have biological or nonbiological origins. Data from Curiosity reveal that billions of years ago, a water lake inside Gale Crater held all the ingredients necessary for life, including chemical building blocks and energy sources. While not necessarily evidence of life itself, these findings are a good sign for future missions exploring the planet's surface and subsurface.

Complex Organics Bubble Up from Ocean World Enceladus

Data from NASA's Cassini spacecraft revealed complex organic molecules originating from Saturn's icy moon Enceladus, strengthening the idea that this ocean world hosts conditions suitable for life. Powerful hydrothermal vents mix up material from the moon's water-filled, porous core with water from the moon's massive subsurface ocean—and it is released into space, in the form of water vapor and ice grains. Scientists analyzed the makeup of the ejected ice and identified fragments of large, complex chemicals. Complex molecules comprising hundreds of atoms are rare beyond Earth. The presence of the large, complex molecules, along with liquid water and hydrothermal activity, bolsters the hypothesis that the ocean of Enceladus may be a habitable environment for life.

Juno Solves 39-Year-Old Mystery of Jupiter Lightning

Lightning bolts act like radio transmitters, sending out radio waves when they flash across the sky. But lightning signals on Jupiter collected by Voyagers 1 and 2, Galileo, and Cassini were limited to either visual detections or signals from the kilohertz range of the radio spectrum, rather than the megahertz range as scientists would expect. The Juno mission, which arrived at Jupiter in July 2016, carried the Microwave Radiometer Instrument, and it was able to detect lightning discharges in the megahertz and gigahertz range. Scientists think the detections were possible because Juno was flying closer to the lightning than ever before and was searching a radio frequency that could pass easily through Jupiter's ionosphere.

Icy Dunes on Pluto Reveal a Diverse and Dynamic Dwarf Planet

Newly discovered dunes on Pluto tell us that the dwarf planet's geology and atmosphere are far more dynamic than previously expected, with the winds of its thin and multi-layer atmosphere helping shape the landscape. These formations appear to be quite young in geological terms, on the scale of decades or centuries old. NASA New Horizon's scientists found these evenly spaced ridges on Pluto's surface using imagery from the 2015 flyby. The ridges appear to have formed out of particles of methane ice as small as grains of sand, arranged into dunes by wind from the nearby mountains.

Astrophysics

The goal of NASA's Astrophysics Division (APD) is to discover how the universe works, explore how it began and evolved, and search for life on planets around other stars. It collects data using an array of space-based observatories, as well as sounding rockets, high-altitude balloons, and the world's largest airborne observatory. ADP supports research that provides insight into our universe and advances the search for life elsewhere.

In April 2018, NASA launched the Transiting Exoplanet Survey Satellite (TESS), a mission to find worlds beyond our solar system, including some that could be potentially habitable. TESS began its science operations in July 2018. The mission will spend the next two years monitoring the nearest and brightest

stars for periodic dips in their light. These events, called transits, are caused by a planet passing in front of its star. Using this method, TESS is expected to find thousands of planets, many of which can then be studied in more detail by the Hubble Space Telescope and the James Webb Space Telescope, as well as ground-based observatories.

Astrophysics is utilizing innovative methods to collect data. HaloSat, a CubeSat designed to detect the halo of hot gas surrounding the Milky Way, was released from the International Space Station in July 2018. The measurements made by HaloSat will help scientists investigate the location of heretofore invisible matter within the universe in the form of x-ray-emitting hot plasma. The High-Resolution Microcalorimeter X-ray Imaging Rocket (Micro-X) launched in July aboard a sounding rocket to test new detector technology. Scientists showed that the sensor could successfully act as a highly sensitive thermometer capable of detecting the energy of a single photon of x-ray light—making an ideal detector for a future x-ray observatory.

NASA's Neutron-star Interior Composition Explorer (NICER) mission, which was installed aboard the International Space Station in June 2017, rapidly made interesting discoveries. Using NICER, researchers discovered two stars located closer together than Earth and the Moon, revolving around each other every 38 minutes. The discovery, published in May 2018, bestows the stellar pair with the record for the shortest known orbital period for a certain class of pulsar binary system. NICER's ongoing mission is to provide high-precision measurements to further study the physics and behavior of neutron stars.

NASA's collection of long-operating space observatories continued to make important contributions to astrophysics. In October 2017, after nearly a decade in space, Fermi contributed to the first joint observations of light and gravitational waves produced by the same event. Fermi was the first observatory to pick up the pulse of high-energy light, which was immediately reported to astronomers around the globe as a short gamma-ray burst. The scientists at the National Science Foundation's Laser Interferometer Gravitational-Wave Observatory (LIGO) detected gravitational waves from the gravitational wave source, a pair of merging neutron stars, tied to the gamma-ray burst. The detection of light from a gravitational-wave-emitting event has revealed details of the event that complement information obtained from gravitational waves.

Scientists used data from NASA's Nuclear Spectroscopic Telescope Array (NuSTAR) space telescope to show that Eta Carinae, the most luminous and massive stellar system within 10,000 light-years, is accelerating particles to high energies—some of which may reach Earth as cosmic rays. Scientists know that high-energy cosmic rays come to Earth from beyond the solar system, but because their paths are affected by galactic magnetic fields, determining the origin of these particles is challenging. The study showed that extreme environments, such as that at Eta Carinae, are one source of these particles.

Observations by NASA's Swift spacecraft, renamed the Neil Gehrels Swift Observatory in 2018 after the mission's late Principal Investigator, have captured an unprecedented change in the rotation of a comet. In a paper published in January 2018, scientists showed that images taken in May 2017 reveal that comet 41P/Tuttle-Giacobini-Kresák was spinning three times slower than it was in March, when it was observed by the Discovery Channel Telescope at Lowell Observatory in Arizona. The abrupt slowdown is the most dramatic change in a comet's rotation ever seen. Scientists believe the change may be caused by jets of dust particles and icy grains that erupt as the comet nears the Sun. The increased heat causes its surface ice to change directly to a gas.

NASA's Chandra X-ray Observatory, which has been operating for nearly 20 years, was used to study a cold front, located in the hot intergalactic gas that pervades the Perseus galaxy cluster, that extends for about two million light years, or about ten billion billion miles. The enormous cold front studied with Chandra formed about five billion years ago and has been traveling at speeds of about 300,000 miles per hour ever since. Surprisingly, the front has remained extremely sharp over the eons, rather than becoming fuzzy or diffuse. Scientists are continuing to study what makes this cold front so resilient.

Nearing 30 years on orbit, NASA's Hubble Space Telescope continued to provide a window to amazing phenomena within our universe, detecting the farthest star ever seen, a globular cluster full of the oldest stars in our galaxy, a collection of "homeless" stars strung out between galaxies, and many other interesting phenomena. In May 2018, an international team of astronomers released the most comprehensive, high-resolution ultraviolet-light survey of nearby star-forming galaxies, based on Hubble data. One of the key questions the survey may help astronomers

answer is the connection between star formation and the major structures, such as spiral arms, that make up a galaxy.

NASA's next large space observatory, the James Webb Space Telescope, completed its cryospheric testing in November 2017. Subsequently, it was determined that final integration and testing will require additional time, and following a review by an Internal Review Board, a revised launch date was established for March 2021. The first telescope of its kind, and an unprecedented feat of engineering, Webb is at the very leading edge of technological innovation and development. When complete, Webb will shed light on many mysteries of the universe, from detecting the light of the first stars and galaxies in the distant universe to probing the atmospheres of exoplanets for possible signs of habitability.

NASA's Astrophysics Division has advanced our understanding of our universe and the search for life throughout FY 2018. Below are five research highlights.

Dark Matter Goes Missing in Oddball Galaxy

Astrophysics theory suggests that every galaxy has dark matter and that dark matter is how a galaxy begins. However, researchers faced a challenge to that theory when data from the Hubble Space Telescope, as well as ground-based telescopes, showed a galaxy that is missing most, if not all, of its dark matter. The unique galaxy, called NGC 1052-DF2, contains at most ¼₀₀ the amount of dark matter that astronomers had expected. The Hubble image also showed that the galaxy is so sparse that one can see all of the galaxies behind it. It does not have characteristics of a spiral, elliptical, or other traditional galaxy shape. Further analysis of this mysterious galaxy will help scientists better understand the role of dark matter in galaxy formation.

NASA Finds a Large Amount of Water in an Exoplanet's Atmosphere

Researchers using data from the Hubble and Spitzer Space Telescopes detected water in the atmosphere of a hot, bloated, Saturn-mass exoplanet about 700 light-years away. Although the planet is similar to Saturn in size, it is 20 times closer to its star than Earth is to the Sun, and it has significantly more water, which suggests that it must have formed differently. The research demonstrates that studying exoplanets can help us to better understand our own solar system and suggests

that planet formation is more complicated than we originally thought. Scientists hope to use the Webb Space Telescope to gather more detailed information on the exoplanet to better understand where and how the planet formed.

Improved Hubble Yardstick Gives Fresh Evidence for New Physics in the Universe

Astronomers have used NASA's Hubble Space Telescope to make the most precise measurements of the expansion rate of the universe since it was first calculated nearly a century ago by Edwin Hubble himself, the Hubble Space Telescope's namesake. The team's new study extends precise geometric measurements of stellar distance to stars up to ten times farther into space than previous Hubble studies. The value reinforced the disparity with the expected value derived from observations of the early universe's expansion, 378,000 years after the Big Bang, made based on measurements from the European Space Agency's Planck satellite. The difference between the two values is about 9 percent. This finding is forcing astronomers to consider that they may be seeing evidence of something unexpected at work in the universe and may signal the need for new physics to explain the inconsistency.

New Clues to TRAPPIST-1 Planet Compositions and Atmospheres

It has been a year since scientists discovered the TRAPPIST-1 system of seven Earth-sized planets. In that time, scientists have used a combination of space- and ground-based telescopes to learn more about this planetary system. Using data from NASA's Spitzer and Kepler Space Telescopes, along with detailed computer models, researchers determined that all of the planets are made of mostly rock. Additionally, some have up to five percent of their mass in water, which would be 250 times more water than the oceans on Earth. For the planets closest to the star, this water is likely in vapor form, while for those farthest away, it is probably frozen as ice on the surface. At least one of the exoplanets is in the habitable zone, and this has a surface temperature conducive to hosting liquid water.

No Planets Needed: NASA Study Shows Disk Patterns Can Self-Generate

Young stars are often surrounded by disks of dust and gas. When scientists detect patterns in the debris—such as rings, arcs, and spirals—they believe these are caused by an orbiting world. However, new analysis shows that these features may

form without the involvement of planets. NASA scientists using complex computer simulations found that high-energy ultraviolet light might drive the creation of patterns in the gas and dust that make up circumstellar disks. The light heats the gas, which causes it to capture more dust, which in turn heats more gas. This cycle can work in tandem with other forces to create some of the features astronomers have observed in debris disks.

Aeronautics Research Mission Directorate

NASA's Aeronautics Research Mission Directorate (ARMD) remained committed to fulfilling its critical research commitments during FY 2018, all of which are intended to transform aviation in ways that directly meet the ever-evolving needs of industry, sustain the highest levels of safety, and maintain the Nation's reputation as the world's leader in all things related to flight operations and aeronautical innovation.

Those research commitments continue to be dominated by the long-term investigations necessary to achieve improvements in aircraft design and propulsion methods (including revolutionary use of electric propulsion) that will enable new opportunities for passenger mobility and cargo, significantly reduce the Nation's reliance on petroleum-based fuel, diminish the amount of potentially harmful emissions released into the atmosphere, and shrink annoying noise levels—especially those heard immediately next to airports during takeoffs and landings.

NASA also remains steadfast in its commitment to working with industry and academia in supplying technical solutions to the Federal Aviation Administration (FAA) for its Next Generation Air Transportation System. More efficient methods for managing air traffic using NASA-developed software were tested in the field during FY 2018 and, in one case, officially transferred to the FAA for further testing and implementation.

Key highlights of NASA's aeronautical achievements during FY 2018 include awarding Lockheed Martin Aeronautics Company a contract to build the X-59 Quiet Supersonic Technology (QueSST) aircraft as the Agency works toward enabling commercial supersonic air travel over land. Another major focus was NASA's ongoing leadership in the fast-growing demand for safely integrating the

use of Unmanned Aircraft Systems (UAS), commonly called "drones," throughout the National Airspace System, including above densely populated areas—what is now called Urban Air Mobility.

Quiet Supersonic Flight Over Land

Involving teams from the Advanced Air Vehicles Program and the Integrated Aviation Systems Program, the Low-Boom Flight Demonstration mission was active in preparing for its comprehensive, scientifically driven effort to provide U.S. and international regulators with statistically valid data required to approve new rules that will allow commercial supersonic flight over land. The centerpiece of this mission is the X-59 QueSST, an experimental supersonic aircraft shaped to reduce the loudness of a sonic boom reaching the ground to that of a gentle thump, if it can be heard at all. Once completed, the X-59 will be flown above select U.S. communities to measure public response to its noise while flying supersonic. A one-of-a-kind airplane, the X-59 officially received its historic X-plane number designation from the Air Force during FY 2018, shortly after NASA awarded the construction contract to Lockheed Martin. More information is available online at *https://www.nasa.gov/lowboom/new-nasa-x-plane-construction-begins-now* and *https://www.nasa.gov/aero/nasa-experimental-supersonic-aircraft-x-59-quesst*.

In preparation for flying the X-59 in about three years, NASA in FY 2018 used its F/A-18 supersonic research jet in ongoing flight tests to better understand how sonic booms propagate through the turbulent atmosphere. Having already conducted a series of research flights during 2016 in the dry air over Edwards Air Force Base in California, the Sonic Booms in Atmospheric Turbulence research team deployed for two weeks in August 2017 to fly in the humid air over Kennedy Space Center in Florida. Repeating the same series of supersonic flights in the tropical environment helped researchers validate tools and models necessary for aiding in the design and operation of the X-59. The Florida visit also provided valuable experience in managing public awareness and reaction to the sonic booms, experience that will be fruitful when the F/A-18 is deployed to Galveston, Texas, in FY 2019 to test methods for gathering public response to any supersonic-related noise they might or might not hear. More information is available online at *https://www.nasa.*

gov/centers/armstrong/features/sonic_boom_tests_set_for_ksc.html and *https://www.nasa.gov/aero/nasa-prepares-to-go-public-with-quiet-supersonic-tech*.

Urban Air Mobility

NASA aeronautical innovators representing all four of ARMD's programs at the four NASA Field Centers where aeronautics research is dominant came together in FY 2018 to address how the Agency can best serve the needs of industry when it comes to UAS. Particular emphasis was placed on the convergence of technologies and new business models enabled by the digital revolution that is making it possible to explore new ways for people and cargo to move within cities—an idea increasingly known as Urban Air Mobility (UAM).

Public-private partnerships are essential to ensuring safe, efficient UAM operations in populated areas. To that end, NASA during FY 2018 signed its second Space Act Agreement with Uber Technologies, Inc. Under this agreement, Uber will share its plans for implementing an urban aviation rideshare network. NASA will use the latest in airspace management computer modeling and simulation to assess the impacts of small aircraft—from delivery drones to passenger aircraft with vertical takeoff and landing capability—in crowded environments. This is NASA's first such agreement specifically focused on modeling and simulation for UAM operations.

More information is available online at *https://www.nasa.gov/aero/taking-air-travel-to-the-streets-or-just-above-them* and *https://www.nasa.gov/press-release/nasa-uber-to-explore-safety-efficiency-of-future-urban-airspace*.

Electric Propulsion

NASA engineers reached a major milestone in FY 2018 with the successful testing of the battery system that will power NASA's first all-electric X-plane, the X-57 Maxwell. The testing validated that the battery system has the necessary capacity to safely power NASA's first piloted X-plane in two decades for an entire flight profile. The test also confirmed the battery design's ability to isolate potential overheating issues to single battery cells, preventing unsafe conditions from spreading to the rest of the battery system.

The first test performed was a battery functional test, which examined the battery's capacity, demonstrating the ability of the battery to power the aircraft for the duration of a flight without overheating to unsafe levels. The X-57 will be powered using lithium-ion batteries that will warm up as they discharge during flight. The second test, known as a thermal runaway and propagation test, was critical in validating the redesign of the battery system, which took place following the results of similar testing in December 2016. While the tests were successful, subsequent data analysis and tests of the redesign prompted further study and refinements. NASA has contributed significantly to community understanding of the challenges and solutions to using these technologies in aviation through extensive publication of research and community engagement.

More information is available online at *https://www.nasa.gov/centers/armstrong/feature/X-57_battery_major_milestone.html* and *https://www.nasa.gov/centers/armstrong/news/FactSheets/FS-109.html*.

Highlights from NASA ARMD's Programs

Advanced Air Vehicles Program

NASA's Commercial Supersonic Technology project in FY 2018 continued developing technologies focused on reducing the noise produced by the exhaust of a supersonic aircraft's jet engines, especially during takeoff and landing. Acoustics experts in NASA's Aero-Acoustic Propulsion Laboratory completed an evaluation of a small-scale model of a jet engine in a simulated environment. Results helped researchers determine how well noise levels produced in a laboratory can be compared to noise data gathered during actual flight tests. More information is available online at *https://www.nasa.gov/image-feature/evaluating-the-noise-of-future-aircraft*.

In FY 2018, NASA flight tests successfully demonstrated technologies that significantly reduce aircraft noise over communities near airports. The technologies, collectively known as Acoustics Research Measurements, addressed airframe noise produced by nonpropulsive parts of an aircraft during landing. Using a Gulfstream III research aircraft, NASA tested experimental designs on several airframe components. These included NASA's Landing Gear Noise Reduction technology, which featured sound-absorbing foam and porous fairings

that reduce noise without increasing drag, and the Adaptive Compliant Trailing Edge wing flap, a seamless, flexible design that reduced noise by eliminating gaps between flaps and the wing body during takeoff and landing. During testing, the aircraft flew at an altitude of 350 feet over an array of 185 microphones. The technologies tested produced a greater-than-70-percent reduction in airframe noise. More information is available online at *https://www.nasa.gov/press-release/nasa-technologies-significantly-reduce-aircraft-noise*.

In FY 2018, NASA and the German Aerospace Center (DLR) continued their collaborative research into alternative aircraft biofuels. In a series of flight tests to analyze engine performance, emissions, and contrail formation, DLR's Advanced Technology Research Aircraft A320 burned alternative biofuels while NASA's DC-8 "Flying Laboratory" trailed behind to gather emissions samples and take measurements. The data will be analyzed to determine how soot from emissions affects contrail ice particles. Previously, the two agencies collaborated in the NASA-led Alternative Fuel Effects on Contrails and Cruise Emissions I and II programs. Those flight tests determined that using a 50/50 blend of biofuel and regular fuel to power jet engines significantly reduced soot emissions. More information is available online at *https://www.nasa.gov/aero/nasa-takes-international-aviation-research-to-the-max*.

Airspace Operations and Safety Program

NASA and Alaska Airlines during FY 2018 tested cockpit-based software developed to help pilots determine the most fuel-efficient routes during flight. The Traffic Aware Strategic Aircrew Requests (TASAR) research project employed the Agency's Traffic Aware Planner (TAP) software, which merged and evaluated real-time data to obtain optimized flight plan options. TASAR improved the process pilots used to request flight paths and altitude modifications based on changing flight conditions as directed by Air Traffic Control (ATC). Typically, pilots make these requests with limited awareness of local flight conditions. Consequently, some requests are denied, resulting in no flight improvements and unnecessary increases in workload for both pilots and the ATC. During testing, TAP software onboard Alaska Airlines aircraft successfully made rerouting recommendations that saved fuel; lowered emissions; and

reduced flight time, operating costs, and environmental impact of the test planes. More information is available online at *https://www.nasa.gov/feature/langley/nasa-and-alaska-airlines-test-software-that-saves-time-fuel*.

A three-year-long demonstration of a new suite of air traffic management technologies at the Charlotte-Douglas International Airport in North Carolina successfully concluded its first year of operations during FY 2018. Known as Airspace Technology Demonstration–2, the software solutions are designed to better manage air traffic to and from an airport, with an emphasis on more efficiently handling aircraft movements between the terminal gate and runway. The shakedown of technology and new procedures involved NASA closely working with the Federal Aviation Administration, the air traffic controllers union, American Airlines, and officials at Charlotte. More information is available online at *https://www.nasa.gov/aero/nasa-air-traffic-management-demo-goes-live*.

NASA partnered with Honeywell in FY 2018 to test an aircraft engine in a high-altitude environment to explore ice crystal icing, a phenomenon that occurs when ice crystals enter an engine's core and accrete. The accumulated ice can cause loss of thrust, stall, surge, and potential damage when ice particles break up and pass through the engine's fan. During testing, researchers identified conditions under which engine ice forms and manipulated variables like temperature and engine fan speed to observe how icing behavior changes. More information is available online at *https://www.nasa.gov/feature/nasa-glenn-tests-aircraft-engines-in-an-ice-crystal-environment*.

Integrated Aviation Systems Program

The centerpiece of the Low-Boom Flight Demonstration mission—the X-59 QueSST aircraft—evolved in FY 2018 from its beginning as a theoretical design on paper to the next step in producing a real flying machine when the Low-Boom Flight Demonstration project awarded a $247.5 million construction contract to Lockheed Martin Aeronautics Company of Palmdale, California. The contract award was a significant milestone in NASA's historic return to flying experimental aircraft. In addition to the fabrication and assembly of the X-59, the contract also calls for Lockheed to orchestrate the initial flight tests that will demonstrate that it is safe to fly and meets all of NASA's performance

requirements. More information is available online at *https://www.nasa.gov/lowboom/new-nasa-x-plane-construction-begins-now.*

NASA in FY 2018 selected three companies to collaborate in the area of UAS flights in the National Airspace System. They will work together to tackle key challenges that prevent routine commercial UAS operations today, including the development, integration, and certification of unpiloted aircraft and avionics. Known as Systems Integration and Operationalization, this research is to cumulate in multiple flight demonstrations in 2020 that focus on UAS missions occurring at altitudes greater than 500 feet above ground level and include integrated Detect and Avoid and Command and Control technologies. More information is available online at *https://www.nasa.gov/centers/armstrong/news/newsreleases/2018/18-18.html.*

NASA's remotely piloted Ikhana aircraft successfully flew its first mission in the National Airspace System without a safety chase aircraft. The milestone flight was conducted to help the United States normalize and open new uncrewed aircraft operations in the airspace used by commercial and private pilots. The Ikhana flew into airspace typically reserved for commercial airliners and communicated in real time with airport air traffic controllers throughout various points of its flight. Prior to the Ikhana's inaugural solo flight, the FAA granted NASA special permission to use the latest Detect and Avoid technologies, which enabled the remote pilot on the ground to see and avoid other aircraft during the flight. More information is available online at *https://www.nasa.gov/press-release/nasa-flies-large-unmanned-aircraft-in-public-airspace-without-chase-plane-for-first*.

Transformative Aeronautics Concepts Program

In the fourth year of NASA's Convergent Aeronautics Solutions (CAS) project, which is designed to identify and nurture "out-of-the-box" thinking about technology that might help transform aviation, three new ideas were selected for study to determine if they are technically feasible and perhaps worthy of additional pursuit within NASA or industry. The selections represented a broad range of research topics, yet each could significantly contribute to building future aircraft that are more energy-efficient, produce fewer emissions, and are quieter. The selected projects involved developing a new assembly technique with composites, finding ways to reduce and shed heat generated by an electric motor, and exploring the

use of a water-based solution for generating electricity to replace lithium-based batteries. More information is available online at *https://www.nasa.gov/aero/nasa-selects-three-ideas-to-pursue-that-could-transform-aviation*.

Significant advances in electric propulsion technology took place in FY 2018, as NASA tested motors and motor controllers that will power the first fully electric X-plane, the X-57 Maxwell. Engineers used a test stand called Airvolt to measure system voltage, current, temperature, vibration, torque, and thrust. These data were used to analyze electric propulsion system efficiency and to determine whether motor components can operate within high- and low-temperature limits. One objective of Airvolt testing and future X-57 research flights is to help the flight certification community identify and establish airworthiness standards for the future. The data gathered by these efforts will be provided to the certification community to help establish airworthiness standards for future electric aviation. More information is available online at *https://www.nasa.gov/centers/armstrong/feature/All-electric_X-57_Cruise_Motors_Begin_Testing.html*.

As part of the Spanwise Adaptive Wing (SAW) project, NASA researchers in FY 2018 conducted flight tests using new technology that allowed a small UAS to fold its wings during flight for improved aerodynamics. The technology employed a lightweight, thermally triggered shape memory alloy to fold the outer portions of wings from zero to 70 degrees to obtain optimal angles for improved fuel efficiency and controllability, as well as reduced drag. During the tests, researchers flew the small UAS called Prototype Technology-Evaluation Research Aircraft, a "flying laboratory" that is ideal for gathering SAW data. More information is available online at *https://www.nasa.gov/centers/armstrong/feature/nasa-tests-new-alloy-to-fold-wings-in-flight.html*.

Space Technology Mission Directorate

The Space Technology Mission Directorate (STMD) develops and incorporates transformative space technologies to enable NASA's future missions. STMD has developed a diverse technology portfolio, creating a pipeline to solve the Nation's most difficult challenges in space. Space technology is an investment in our Nation's high-tech economy, spurring innovation and building partnerships across the aerospace sector and beyond.

In FY 2018, STMD made significant progress toward advancing NASA's current and future deep space exploration missions. In order to enable and enhance the Agency's capabilities, investments focused primarily on five strategic thrust areas:

Presently, STMD has over 1,000 active project activities led by more than 400 companies and over 360 activities led by more than 120 academic institutions. In addition, STMD is partnered with 15 other Government agencies or departments as well as four international organizations. In FY 2018, STMD evaluated over 3,600 proposals and funded new technology selections, amounting to over $380 million in award investments.

In 2018, 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, live, and explore the Moon and Mars.

Tipping-Point Partnerships

In August, STMD announced its partnerships with six U.S. companies to develop 10 "tipping point" technologies that have the potential to significantly benefit the commercial space economy and future NASA missions, including lunar lander and deep space rocket engine technologies. These awards focus on technology collaborations with the commercial space sector that leverage emerging markets and capabilities to meet NASA's exploration goals. While these key technologies will support NASA's science and human exploration missions in the future, these awards also showcase NASA's commitment to the Nation's growing commercial space industry today.

Technology Demonstration Missions (TDMs)

Deep Space Atomic Clock (DSAC): The DSAC project will fly and validate 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. The clock will provide enhanced navigation accuracy, increased science data bandwidth, and improved gravitational measurements

necessary for future planetary science and exploration missions. In FY 2018, the DSAC payload successfully completed its final integrated verification testing and successfully passed the Mission Readiness Review (MRR). DSAC remains in clean room storage, awaiting a 2019 launch on the U.S. Air Force's Space Test Program (STP)–2 mission aboard a SpaceX Falcon Heavy.

Green Propellant Infusion Mission (GPIM): The GPIM spacecraft—designed to test the unique attributes of a high-performance, nontoxic, "green" fuel on orbit—completed all flight system integration and test activities and is ready for launch next year. The propellant, a hydroxyl ammonium nitrate–based fuel/oxidizer mix also known as AF-M315E, can replace the highly toxic hydrazine and complex bipropellant systems in use today, providing enhanced performance and volumetric efficiency. The spacecraft is being maintained in readiness for a launch to low-Earth orbit in 2019 in partnership with the U.S. Air Force's STP-2 mission aboard a SpaceX Falcon Heavy.

Laser Communication Relay Demonstration (LCRD): The LCRD mission proposes to revolutionize the way we send and receive data, video, and other information, using lasers to encode and transmit data at rates 10 to 100 times faster than today's fastest radio-frequency systems, with significantly less mass and power. The LCRD project continues to meet developmental milestones on its way to a launch in 2020 to demonstrate bidirectional optical communications from geosynchronous orbit, providing critical performance data and operational experience. In FY 2018, the project completed system integration and functional and environmental testing, and it is preparing to deliver the flight payload to the spacecraft integrator in FY 2019 to support a No Earlier Than (NET) April 2020 Launch Readiness Date.

In-Space Robotic Manufacturing and Assembly: The three project teams have completed the final year of the two-year Phase 1 effort. The Made In Space Archinaut team completed thermal-vacuum testing of the Ground Based Manufacturing and Assembly System Hardware (GBMASH) to demonstrate additive manufacturing and assembly of structures in a relevant, spacelike environment. The Space Systems Loral (SSL) Dragonfly team completed reviews of system requirements, verification plans, performance, interfaces, and hardware robotic assembly designs, and they successfully demonstrated in-space manufacturing mechanisms and conducted a successful Phase 1 closeout review. The Northrop

Grumman Commercial Infrastructure for Robotic Assembly and Services (CIRAS) project advanced in-space assembly components and processes, including demonstrations of a robotic arm, end effectors, assembly tools, reversible joining methods, control software, a quick-disconnect interface, and modular truss structures. Phase 2 selections are pending.

Robotic Refueling Mission 3 (RRM3): RRM3 builds on the first two phases of International Space Station (ISS) technology demonstrations that tested tools, technologies, and techniques to refuel and repair satellites in orbit. RRM3 will demonstrate innovative methods to store, transfer, and freeze standard cryogenic fluid in space. The project completed payload integration and environmental testing on all hardware. The hardware will launch on the SpaceX CRS-16 mission in December 2018.

Restore-L: The Restore-L mission's objective is to refuel a U.S. Government satellite in low-Earth orbit, demonstrating a suite of satellite-servicing technologies and potentially enabling the burgeoning U.S. satellite-servicing industry. The project has been working on integrated design, development, testing, and evaluation. In FY 2018, the project successfully completed an end-to-end demonstration of an autonomous capture with a LandSat 7 mock-up and a payload simulator. The project has begun a suite of subsystem reviews as it is readying for mission-level review in FY 2019.

LEO-based Flight Test of an Inflatable Decelerator (LOFTID): The LOFTID project became part of the TDM portfolio in FY 2018. The objective is to demonstrate a Hypersonic Inflatable Aerodynamic Decelerator (HIAD) to mature inflatable aeroshell technology for future NASA heavy down-mass missions and commercial applications. In early FY 2018, contractors were selected: Airborne Systems, Inc., to provide the reentry vehicle inflatable structure and Jackson-Bond Enterprises to supply the flexible thermal protection system. An agreement has also been finalized with industry partner United Launch Alliance (ULA). The project defined functional and performance requirements and developed preliminary project plans, culminating in a successful System Requirements Review in May. Fabrication of the reentry vehicle Engineering Development Unit (EDU) is under way, as well as the avionics subsystem design. The preliminary design of the system is also in progress, with the Preliminary Design Review scheduled for February 2019.

Evolvable Cryogenics (eCryo): In FY 2018, the eCryo team conducted ground testing of the Radio Frequency Mass Gauge (RFMG) flight hardware with RRM3. Final testing and reporting on advanced cryogenic insulation systems was completed as part of the Improved Fundamental Understanding of Super Insulation (IFUSI) task. Preparations for FY 2019 Structural Heat Intercept, Insulation Vibration Evaluation Rig (SHIIVER) testing continued. The foam-insulated SHIIVER tank, thermal test support stand, forward skirt (with vapor-cooling heat-intercept channels) and skirt multi-layer insulation have been delivered to Plum Brook Station for assembly and integration. Fabrication of the remaining SHIIVER components is under way. Cryogenic Fluid Management modeling and analysis collaboration with JAXA continued in 2018.

Game Changing Development (GCD)

The **Kilopower** project objective is to demonstrate a compact, safe, scalable space fission power system to enable crewed surface missions on planetary bodies. The NASA and Department of Energy team successfully completed the Kilopower Reactor Using Stirling Technology (KRUSTY) full-power test of a 1-kilowatt reactor over a two-day period in March at the Nevada National Security Site (NNSS). The project employed the novel integration of available uranium-235 fuel form, passive sodium heat pipes, and flight-ready convertors. The KRUSTY experiment is the first fission nuclear reactor test in over 50 years.

The **Adaptable, Deployable Entry and Placement Technology (ADEPT)** project's objective is to advance heat shield technology for planetary landers and sample return missions. The ADEPT flight test was conducted on September 12 aboard an UP Aerospace sounding rocket. It achieved full deployment and performed as expected, and all data sources were recovered. The team will continue to analyze the data in the coming months.

The **Low-Cost Upper Stage-Class Propulsion (LCUSP)** project was a five-year effort to develop and demonstrate additive manufacturing processes to produce rocket propulsion components in less time and at a lower cost than conventional manufacturing methods. The LCUSP was a very successful project, having achieved a number of technology firsts, including the use of Selective Laser

Manufacturing (SLM) and Electron Beam Free Form Fabrication in the fabrication of two different combustion chambers. The project successfully achieved its goals and culminated in a successful hot fire test of a 35,000-pound-force combustion chamber and nozzle at NASA's Marshall Space Flight Center on March 2. The team has been successful in infusing technology into industry, leading to growth in advanced manufacturing jobs. Major aerospace prime contractors, such as SpaceX, Orbital ATK, Aerojet-Rocketdyne, ULA, and Blue Origin, are investigating the use of SLM in the production of propulsion components for their vehicles.

Bulk Metallic Glass (BMG) Gears technology offers to develop planetary and strain wave (a.k.a. Harmonic Drive) gearboxes capable of reliable operation at or below 100 kelvins without the use of heaters. The product capability offers a viable gearing technology for power-constrained missions in cryogenic environments such as the Moon during lunar night, permanently shadowed craters, or icy bodies such as Europa. Once fully matured, the technology will enable operation for low-temperature, power-constrained missions such as missions to the Moon. In FY 2018, the project successfully completed cold life testing of planetary gears, both unlubricated and dry-lubricant operation at <100 kelvins and >1 hour.

The **High Performance Spaceflight Computing (HPSC)** project is developing a next-generation flight computing system that addresses the computational performance, energy management, and fault tolerance needs of NASA missions through 2030 and beyond. The Boeing Company was contracted to develop and provide the chiplet, a multicore hardware processor, associated system software and software development environment, an evaluation board, and a software simulator/emulator. In May 2018, the HPSC Project successfully completed the Preliminary Design Review for the HPSC chiplet. This allowed the chiplet design team to begin the register-transfer level (RTL) layouts of the HPSC chiplet subsystems. In July 2019, the HPSC Project is expected to complete the RTL layouts of all chiplet subsystems in preparation for a chiplet Critical Design Review in the fall of 2019.

The **Safe and Precise Landing—Integrated Capabilities Evolution (SPLICE)** project is focused on the development, technology readiness maturation, flight demonstration, and infusion of Precision Landing and Hazard Avoidance (PL&HA) technologies into NASA missions and commercial spaceflight missions. In FY 2018, the project completed the Hardware-in-the-Loop (HWIL) simulation.

This HWIL simulation was integrated with the SPLICE Descent and Landing Computer (DLC). The DLC incorporates a surrogate of the HPSC processor (see above), which will accelerate the integration of the HPSC components on future precision landing and hazard-avoidance demonstrations.

The **Astrobee** project is developing a set of three free-flying robots that will operate inside the ISS alongside astronauts. Astrobee's primary objective is to provide a zero-g research facility for guest scientists. In FY 2018, the project completed building Certification and Flight Units of the Docking Station. The project completed the Free Flyer Certification Unit build and procured and installed the Ground Server that will provide storage for experiment data for the Astrobee facility. Astrobee free flyers will launch in spring 2019 on NG-11 and SpaceX CRS-18.

The **In-Space Manufacturing (ISM)** project is focused on the development and demonstration of advanced manufacturing techniques, including additive manufacturing, to enable on-demand fabrication of components and spare parts in space. ISM is demonstrating these capabilities on the ISS. In FY 2018, ISM awarded three contracts to Techshot, Tethers Unlimited, and Interlog under the NextSTEP Broad Agency Announcement to develop a Multi-material Fabrication Laboratory (FabLab).

Small Business Innovative Research (SBIR) and Small Business Technology Transfer (STTR)

NASA awarded 555 contracts for a total of $180.1 million in FY 2018. Specifically, 304 SBIR and 44 STTR Phase I proposals were selected for award to 277 U.S. small businesses to establish the scientific, technical, and commercial feasibility of each proposed innovation. In addition, 144 SBIR and 24 STTR Phase II awards were selected to further expand upon their Phase I work. Through the Phase II Extended/Expanded program, 39 options were exercised for $10.6 million in SBIR/STTR funding, which was matched by over $7 million from investors outside the program (other NASA programs, other Government agencies, and commercial investors). Additionally, 32 Phase III awards were made leveraging over $7.8 million in non-SBIR/-STTR funding.

A highlight for the year included Pancopia in Hampton, Virginia, who created an innovative water-recycling process that leverages novel microorganisms to provide

cost-effective, closed-loop water purification on the ISS and on Earth. NASA SBIR awarded Pancopia $885,000 to build and expand the prototype. Pancopia received two commercialization awards with the United States Department of Agriculture (USDA) for this new recycling system and has partnered with the USDA to license its patented anammox bacteria.

Small Spacecraft Technology Program (SSTP)

The SSTP launched two successful technology demonstration missions on November 12, 2017, on the Cygnus Resupply Mission (OA-8), later deploying them to low-Earth orbit on December 6, 2017.

The Optical Communications and Sensor Demonstration (OCSD) mission, developed and operated by the Aerospace Corporation, transmitted at an error-free data rate of 200 megabits per second (approximately a 100× increase over CubeSat state of the art) to a 30-centimeter telescope. A second demonstration successfully completed by OCSD's twin 1.5-unit spacecraft involved a propulsive rendezvous with water-fueled maneuvering thrusters to rejoin the spacecraft after a 460-kilometer post-deployment drift to a closest approach of six meters.

The Integrated Solar Array Reflectarray Antenna (ISARA) mission, developed and operated by NASA's Jet Propulsion Laboratory (JPL) and the Aerospace Corporation, is the first in-space demonstration of a Ka-band reflectarray, which is an integrated solar array and radio antenna structure. The reflectarray technology is capable of data rate transmission of up to 100 megabits per second (Mb/s). By integrating the solar panel and antenna structure together, more volume is made available for payloads in the CubeSat structure. The technologies demonstrated on these missions pave the way for high-value science missions and formation flying missions that use distributed CubeSats and small satellites. The technology pioneered for use in spaceflight by the primary ISARA payload, the JPL reflectarray antenna, was an integrated part of the successful data relay by the two MarCO spacecraft during the Insight landing on November 26.

The Pathfinder Technology Demonstrator (PTD) project completed its payload assessment of the Tethers Unlimited, Inc. (TUI), HYDROS water hydrolysis thruster-based propulsion system. The HYDROS system separates onboard water

into hydrogen and oxygen propellants by applying an electric current through the water. The propulsion system uses the on-orbit power provided by the arrays to power a miniature water electrolysis system. The in-space demonstration will test propulsion performance through programmed changes in spacecraft velocity and altitude executed by the water-fueled thrusters. This first PTD mission is slated for launch in 2019.

The program awarded nine university teams to collaborate on the development and demonstration of new technologies and capabilities for small spacecraft. Proposals were awarded in three topic areas: instrument technologies for small spacecraft; technologies that enable large swarms of small spacecraft; and technologies that enable deep space small spacecraft missions. This is the fourth round of projects selected under the Smallsat Technology Partnerships initiative.

Flight Opportunities

In FY 2018, the Flight Opportunities program funded flights on four vertical takeoff/vertical lander flight campaigns, two Suborbital Reusable Launch Vehicle (sRLV) flight campaigns, five high-altitude balloon flights, and two parabolic campaigns for researchers developing technologies that are of interest to NASA and the commercial space industry. The program flew 28 technology payloads in FY 2018 on 17 flights.

- Blue Origin had two successful test flights of its New Shepherd rocket in FY 2018, each carrying Flight Opportunities–funded payloads. In April, a sensor package developed at NASA's Johnson Space Center to study the internal environment of suborbital vehicles as test platforms was tested, as well as wireless technology to perform the world's first commercial tweet from space. The July flight test carried five NASA-supported technologies onboard, and for each of these payloads, the flight was one in a series of suborbital demonstrations to facilitate technology development.
- UP Aerospace launched two of its SpaceLoft rockets for NASA within five days. In addition to testing eight technology payloads, including the ADEPT heat shield, the back-to-back launches demonstrated responsive and rapid relaunch capabilities.

- In May, Masten Space Systems Xodiac rocket-flight-tested HoneyBee Robotics' pneumatic sampler collection system, PlanetVac. PlanetVac is a surface soil–collection system for a sample return mission. This flight provided HoneyBee with the opportunity to test in a situation more realistic to what the payload might encounter on a space mission.
- Two Research, Development, Demonstration, and Infusion (REDDI) parabolic flights tested technologies in propellant gauging and optimizing chilldown methods for cryogenic propellant tanks imperative for efficient fuel transfer in deep space. Also tested were bio-inspired flexible probes for interaction with and anchoring to the surface of asteroids and other low-gravity bodies for sampling operations and collection for In-Situ Resource Utilization (ISRU). The capabilities sought by these technologies—ISRU collection and subsequent storage and transfer of fuel in space—are critical for sustained exploration activities beyond Earth.
- World View Enterprises balloon flights in March and September made strides in advancing technology for understanding planetary evolution by measuring how electromagnetic waves penetrate the surface—and what information that might reveal.

Space Technology Research Grants (STRG)

Since its inception, STRG has funded exciting space technology research via 595 grants at 107 universities across 43 states and one U.S. territory. In FY 2018, the program made 14 Early Stage Innovations awards, 11 Early Career Faculty awards, and 56 NASA Space Technology Research Fellowship awards. The inaugural Space Technology Research Institutes—the Center for Utilization of Biological Engineering in Space (CUBES), led by the University of California, Berkeley, and the Institute for Ultra-Strong Composites by Computational Design (US-COMP), led by Michigan Technological University—both successfully completed the first year of these multi-year awards.

- CUBES, working to advance the practicality of an integrated, multi-function, multi-organism bio-manufacturing system on a Mars mission, demonstrated a microbial electrocatalysis system that reduces Martian

dinitrogen (N_2) levels to the levels needed for sustainable plant production and developed a method to synthesize a bone-regeneration hormone in lettuce leaf tissue as a possible microgravity countermeasure for crew health.

- US-COMP, in its efforts to enable computationally driven development of carbon nanotube (CNT)–based ultra-high-strength lightweight structural materials, demonstrated an improvement in the microstructure of four-ply core-spun yarns, completed preliminary mechanical tests, and fabricated small yarn composite samples.

Other program research highlights include the following:

- Simon Vecchioni from Columbia University grew his own DNA-based biowires, which are 20 times more conductive than normal DNA. Simon demonstrated the first-ever electrically functional DNA nanoelectric components and proved that successful fabrication of biowires is possible in a low-resource environment, such as those that will be encountered on future deep space missions.
- Carmel Majidi from Carnegie Mellon University was featured in a *Washington Post* article for creating self-healing "Terminator skin" that combines electronic circuits, soft sensors, and elastic conductive material. The material can spontaneously repair itself after sustaining damage; Carmel demonstrated the ability to power a clock while simultaneously damaging the conductive connections using a sharp object. Stretchable electronics have potential applications in planetary exploration where resilient, lightweight, and flexible sensors can be worn by bio-inspired soft robots in treacherous environments such as Mars.[1]

NASA Innovative Advanced Concepts (NIAC)

In 2018, NIAC awarded 16 Phase I and nine Phase II awards across industry, academia, and NASA Centers while completing 15 2017 Phase I studies and eight

1 Peter Holley, "Terminator Skin: Researchers Create 'Self-Healing' Material for Robots," *Washington Post* (May 24, 2018), available at *https://www.washingtonpost.com/news/innovations/wp/2018/05/24/terminator-skin-researchers-create-self-healing-material-for-robots/?utm_term=.9a7a590f7cc9* (accessed July 26, 2019).

2016 Phase II studies. In partnership with World Book, NIAC received approvals for a second inspiring eight-book STEM series to further promote NASA science globally, with a theme of "Out of This World." In the series, NASA scientists share their individual stories about how they grew from young students to scientists and how they are working on solving some of NASA's biggest challenges.

Centennial Challenges

The Centennial Challenges program conducted two competition events in FY 2018, awarding $220,000 in prize money. A new competition was launched—the CO_2 Conversion Challenge—and opened for registration. The program also began the formulation and development of two new challenges slated to open in 2019.

- The program began work on creating Phase 2 of the **Space Robotics Challenge**. Phase 1 took place in FY 2017, and 23 teams won a total of $555,000 over the course of the competition. The goal of Phase 2 is to advance robotics software and autonomy, and the goal launch date is in 2019.
- With the preliminary Ground Tournaments ending in FY 2017, **Cube Quest** teams are preparing their CubeSats for the in-space competitions that will begin with the first flight of the Space Launch System, EM-1. The purpose of these Deep Space and Lunar Derbies is to design, build, and launch flight-qualified, small satellites capable of advanced operations near and beyond the Moon.
- Phase 3 of the **3D-Printed Habitat Challenge** opened in November 2017, and teams have competed in two of the five sublevels, winning a total of $220,000 so far. The multi-phase challenge is designed to advance the construction technology needed to create sustainable housing solutions for Earth and beyond. It will culminate in April 2019 with a head-to-head construction demonstration.
- The newest competition—the **CO_2 Conversion Challenge**—launched in August. It is a $1 million competition to convert carbon dioxide into sugars such as glucose as a first step to creating mission-critical resources. Such technologies will allow us to manufacture products using local,

indigenous resources on Mars, and on Earth by using waste and atmospheric carbon dioxide as a resource.

- The **Vascular Tissue Challenge** is ongoing, with 12 teams registered. The goal is to advance the field of tissue engineering by successfully growing thick, vascularized human tissue for a major organ. The prize purse is $500,000.

Technology Transfer

The Technology Transfer program continued to create value for NASA and taxpayers by spinning out an unprecedented number of new technologies. For the seventh year in a row, the program set new records for the volume of technologies shared with partner companies—with 99 new patent licenses and 2,987 software usage agreements. This year's totals were helped along by the release of a new software catalog and the launch of an automated online licensing application tool.

iTech

The iTech program—a collaborative effort that identifies and fosters innovative solutions for solving challenges on Earth and also in space—conducted three cycles of competitions in FY 2018, including one with the U.S. Department of Energy's Advanced Research Projects Agency–Energy (ARPA-E) to identify transformational energy technologies that can improve energy generation, storage, and distribution to the benefit of both space exploration and life on Earth.

Department of Defense

DOD

Aeronautics

Rotorcraft

Army

The United States Army (USA) is continuing its modernization efforts across the entire aviation fleet. Rotary-wing aircraft fielding of the AH-64E Apache, UH-60M Blackhawk, CH-47F Block II Chinook, HH-60V MEDEVAC Blackhawk, and LUH-72 Lakota will ensure that Army aircraft will be capable for decades to come.

The USA Joint Multi-Role Technology Demonstrator (JMR-TD) demonstrated progress in support of technology development for Future Vertical Lift (FVL). Although not flying demonstrators, vendors have produced significant technology advancements in tiltrotor and coaxial rotor technology as well as actuator designs. Additional efforts include the Mission System Architecture Demonstration. This collaborative industry effort is developing an open system architecture for future platforms across the Department of Defense.

Navy

The United States Navy (USN) CH-53K Super Stallion program reached a major milestone as it began low-rate initial production. 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 shifted from the contractor facility in West Palm Beach, Florida, to Naval Air Station Patuxent River, Maryland.

The VH-92 Presidential Helicopter Replacement commenced Integrated Government Flight Test in August 2018. The program received a successful Milestone C decision in May 2019 authorizing Low-Rate Initial Production of the first six operational aircraft.

The V-22 Osprey has been in production for several years, with more than 350 aircraft delivered to the United States Marine Corps (USMC) 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 USN has delivered 526 of 555 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 out to 2040, and establish the foundation to rapidly and 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 intends to pursue a nondevelopmental approach and procure a commercial helicopter.

Air Force

The United States Air Force (USAF) awarded a contract to Boeing on September 24, 2018, to purchase up to 84 helicopters and associated training devices and ground equipment to replace the legacy UH-1Ns. The replacement helicopter meets the need to secure and defend the Nation's intercontinental ballistic missiles (ICBMs) and provide continuity of operations, flights, training, testing, and operational support airlift. The replacement is planned to reach Initial Operational Capability (IOC) in 2023.

Fixed-Wing

Navy

The transition of the P-3C to the P-8A continues to progress, with 74 P-8A aircraft delivered to the USN and four aircraft delivered to the Royal Australian Air Force under a cooperative agreement. The USN has transitioned nine of 12 fleet squadrons with the tenth squadron currently in transition. With over 63 percent of the aircraft delivered, the USN has flown nearly 25,000 sorties and logged over 135,000 flight hours.

DOD completed the System Development and Demonstration (SDD) flight testing phase of the F-35 Joint Strike Fighter (JSF). Naval Air Station (NAS) Lemoore stood up the first USN F-35 Master Jet Base in January 2017 and began training the first operational F-35C squadron in January 2018. In June 2018, the first F-35Bs operationally deployed aboard the USS WASP and USS Essex, conducting operations in the Indian Ocean and the Pacific. In September, USMC F-35Bs were the first U.S. Joint Strike Fighters employed in combat. In August 2018, VFA-125 and VFA-147 participated in the first integrated Carrier Air Wing Operations aboard the USS Abraham Lincoln. In September, two F-35s successfully landed onboard the HMS Queen Elizabeth for the first time, with both USMC and Royal Air Force (RAF) aircraft participating. To date, 320 F-35 aircraft have been delivered, with 91 planned for delivery in calendar year 2019.

The USMC has delivered 54 of 104 KC-130J aircraft, transitioning four active-duty squadrons and one reserve squadron. Concurrently, the USMC began installing the NP2000 eight-bladed propeller on its legacy C-130 fleet.

The USN and USAF are working together on a joint Analysis of Alternatives to determine the best material solution to recapitalize E-6B and other National Command and Control Aircraft.

In March 2018, the USN awarded Boeing a contract to modernize the F/A-18 fleet, extending the life of existing Super Hornets from 6,000 to 9,000+ flight hours. In the early 2020s, Boeing will begin installing initial updates to the aircraft that will convert existing Block II Super Hornets to a new Block III configuration. The Block III conversion will include enhanced network capability, longer range with conformal fuel tanks, an advanced cockpit system, signature improvements, and an enhanced communication system.

The E-2D program has delivered 34 aircraft to date. The USN received approval to award a multi-year procurement in fiscal year (FY) 2019 to build 12 E-2D aircraft. Upgrades to the platform continued in FY 2018 as the Navy released Delta Software System Configuration 2, allowing the E-2D to pace the evolving threat.

Air Force

The USAF awarded a contract to Boeing on September 27, 2018, to purchase 351 aircraft, 46 associated training devices, and other ancillary supplies and service to replace Air Education and Training Command's fleet of T-38C training aircraft. The Advanced Pilot Training program is expected to provide student pilots in undergraduate- and graduate-level training courses with the skills and competencies required to transition to fourth- and fifth-generation fighter and bomber aircraft. The USAF plans to achieve Initial Operational Capability in 2024.

Low Cost Attritable Aircraft Technologies (LCAAT) is an Air Force Research Laboratory (AFRL) effort focused on reducing the cost of building an aircraft airframe by more than a factor of ten. LCAAT will enable a family of limited-function, rapidly produced, low-cost, attritable Unmanned Aerial Vehicles (UAVs) to augment piloted weapon systems to force a cost-imposition effect on near-peer adversaries. The effort completed vehicle build and is currently in testing, with first flight test to occur in late 2018.

Unmanned Aircraft Systems (UAS)

Army

The USA continues to modernize the MQ-1C Gray Eagle and RQ-7B Shadow UAS in stride with combat operations. In August 2018, the Army fielded its 14th Gray Eagle Company (15 total) and has begun transitioning units to the new Extended Range Gray Eagle, which increases the endurance to 41 hours. Gray Eagle units are assigned to Active Army Divisions, the Intelligence and Securities Command (INSCOM), and the 160th Special Operations Aviation Regiment. The Shadow is nearing the end of its modernization in FY 2019 with the fielding of the remaining RQ-7B V2. That upgrade includes a new universal ground control station. Additionally, in FY 2019, the USA will begin experimenting on a future tactical UAS 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 systems 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 family of systems, and it will provide combat information to operational and tactical users such as the Expeditionary Strike Group, Carrier Strike Group, and Joint Forces Maritime Component Commander. Developmental testing on the baseline capability was completed in October 2017, and Early Operational Capability is planned for 2018. The upgraded multiple intelligence capability is on track to support the maritime ISR and targeting 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, a UAV common automatic recovery system for takeoffs and landings, payloads (electro-optical/infrared/laser designator-range finder, automated information system, voice communications relay, radar, coastal battlefield reconnaissance and analysis, and other specialty payloads), and associated spares and support equipment. Fire Scout 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. MQ-8C Initial Operational Capability is scheduled for FY 2019.

The MQ-25 program is rapidly developing an uncrewed 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 these goals through the use of a carrier-suitable, semiautonomous (man-in-the-loop, air vehicle executes preplanned missions) UAS (provided by the Air System segment) and controlled through existing Command, Control, Communications, Computers, and Intelligence (C4I) 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 Assistant Secretary of the Navy for Research, Development, and Acquisitions have approved accelerated, streamlined processes for the program office to move the IOC from FY 2028 to FY 2024. The Government executed 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 (MBSE) and embedded teaming, to keep the program on track to be the fastest contract award-to-IOC of any modern major aviation program.

Weapons

Army

The USA 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. USA Aviation is also developing smaller, more versatile modular missile technology that allows 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 USA began fielding and improving other munitions, including the Joint Air-to-Ground Missile (JAGM) and the Advanced Precision Kill Weapon System (APKWS). JAGM is a multi-mode guidance munition capable of precision point and fire-and-forget targeting. These capabilities can be employed in adverse

weather and against countermeasures while also affording simultaneous engagements on both moving and stationary targets with increased lethality. In 2018, the USA had multiple successful engagements with the APKWS in operational theaters, validating the capability and investments in lighter precision munitions.

Navy

During FY 2017, the USN matured its long-range Cruise Missile Strategy. Key developmental and sustainment tenets of this strategy include support of Tomahawk Land Attack/Block III and Tactical Tomahawk/Block IV (TACTOM) through their anticipated service lives, integration of modernization and obsolescence upgrades to TACTOM during a midlife recertification program (which extends the missile service life an additional 15 years), 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 development of follow-on Next Generation Strike Capability (NGSC) weapons to address future threats and targets. NGSC includes capabilities for both the air-launched Offensive Anti-Surface Warfare (OASuW)/Increment 2 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.

LRASM continues to pioneer advanced semi-autonomous strike weapon capabilities. In FY 2018, LRASM had multiple successes, including a two-weapon salvo that demonstrated autonomous behaviors against multiple moving ships, culminating in a direct hit on the intended target. The LRASM program also delivered the first tactical rounds to support USAF B-1 Early Operational Capability.

The Advanced Anti-Radiation Guided Missile (AARGM)/Block 1 had formal fleet release in the summer of 2017. AARGM is a cooperative development program with the Italian Air Force to transform the High-Speed Anti-Radiation Missile (HARM) into an affordable, lethal, and flexible time-sensitive strike weapon system for conducting Destruction of Enemy Air Defense missions. AARGM adds multispectral targeting capability and targeting geospecificity to its supersonic fly-out to destroy sophisticated enemy air defenses and expands upon the HARM target set.

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 2017, SDB II continued Government confidence tests that had multiple program firsts, including conducting a successful test employment against multiple advanced countermeasures and hitting targets in a cluttered urban environment.

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 is proven in combat for five years. The Advanced Precision Kill Weapon System 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).

Aviation Survivability Equipment

Army

In 2018, the USA 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 USA'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 MANPADSes. Army Aviation will begin receiving production systems of the Common Infrared Countermeasure in early FY 2019.

Army Aviation is also developing requirements for the Advanced Threat Detection System (ATDS) designated as the next-generation missile/threat warning system that will significantly increase the array of threats that can be detected and defeated. ATDS is targeted for fielding in FY 2027 and will also provide greater situational awareness to aircrews against additional threats, such as rocket-propelled

grenades, anti-tank guided missiles, and unguided ballistic projectiles such as heavy, crew-served machine guns.

The USA is also investing in upgraded detection and countermeasures to address Radio Frequency (RF) threats. Radar Warning Receiver (APR-39D[V]2) fielding begins mid-FY 2019 and will continue through FY 2022 as a bridging solution until the Modernized Radar Warning Receiver is fielded. Along with advances in detection capabilities, the USA is also advancing its threat defeat capabilities with the development of a family of Advanced Airborne Expendable Countermeasures. Production on an improved counter-RF expendable countermeasure (chaff) has also commenced and is expected to be fielded to the force in 2024. Upgraded chaff and Electronic Countermeasures fielding will coincide with the improved detection initiatives. Essential to the protection of aircraft against emerging threats, Army Aviation will pursue 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, a 3,000-shaft-horsepower engine, designed to replace the current GE 701D engine that powers the AH-64E and UH-60. This engine will bring new technologies that increase the engine's power and the overall fuel efficiency. This capability will enable the USA to carry required payloads at increased ranges and greatly increased endurance while decreasing the need for the logistics involved in resupplying fuel. The Improved Turbine Engine will also reduce the cost of ownership by increasing engine design life and overall engine reliability through advanced internal aerodynamics, hybrid ceramic bearings, and improved inlet particle separation. Two competing preliminary engine designs were completed in 2018. The downselect to one vender for the Engineering and Manufacturing Development Phase of procurement is expected in January 2019.

Air Force

The USAF Research Laboratory and Honeywell recently completed a preliminary design and will complete a detailed design of the TPE331 Improved Performance Technology Engine (IPTE) in the fall of 2018. The new advanced technologies will take Honeywell's existing TPE331 turboprop engine, which has supported everything from modern-day general aviation aircraft to military uncrewed systems (e.g., the MQ-9 Reaper), and give it 30 percent more power and 15 percent better fuel efficiency while keeping it in the same size and package as the existing engine. With the TPE331 IPTE program, Honeywell's next-generation engine will have the performance and capabilities for continued use in future military missions while finding success and new applications across the commercial industry, such as upgrading twin-engine turboprop aircraft, accelerating performance growth for single-engine platforms, and meeting large-load capacity requirements for agricultural aircraft. The development and testing of the engine will be completed by 2021.

The Supersonic Turbine Engine for Long Range (STELR) successfully completed 57 minutes of a durability engine testing at Mach 2.7. The objective of the STELR project is to demonstrate robust, supersonic expendable turbine engine technologies. Engines using these technologies could be used for long-range supersonic cruise missiles or be the basis for future reusable boosters for reusable hypersonic vehicles in a Turbine-Based Combined Cycle propulsion system.

Hypersonics

Air Force

AFRL, with the Arnold Engineering Development Center (AEDC), successfully reactivated the Von Kármán Facility Wind Tunnel D for use in supersonic and hypersonic research. The tunnel was originally operated from 1953 to 1977 as a low-cost research and customer test facility before lying dormant for nearly 40 years. AFRL led a 2016–18 return-to-service effort as part of a strategy to improve technology transfer between the research and ground-test communities. The building housing Tunnel D was renovated as a collaborative research facility and equipped with new supply infrastructure, state-of-the-art controls, data, and safety systems, as well as a full suite of advanced diagnostics. It now serves as one

of AFRL's platforms for diagnostics development and research in high-speed aerodynamics and fluid-structure interactions.

Building upon initial funding from the Small Business Innovative Research (SBIR) program with Generation Orbit Launch Services, Inc., AFRL awarded a follow-on contract (valued at $11.8 million) to finalize the design and conduct the initial flight test of GOLauncher1 (GO1). The USAF has designated the GO1 hypersonic flight research vehicle as X-60A. GO1 is an air-dropped, liquid-propelled rocket designed for routine and affordable hypersonic flight testing of key hypersonic technologies that cannot be tested in current hypersonic wind tunnels. AFRL completed hot fire testing of the GO1 stage at AFRL's Rocket Lab facilities at Edwards Air Force Base (AFB), California, and a store separation wind tunnel test in Calspan's transonic tunnel in Buffalo, New York. The first flight test of GO1 is scheduled for spring 2019, when it will cruise at Mach 6. Flight testing is planned to be based out of Cecil Field near Jacksonville, Florida. GO1 will provide much more affordable, commercial testing capability available to all parties working on hypersonic technologies and wanting to conduct hypersonic testing. It will become a critical test asset to the Nation.

Space

Science and Technology

Air Force

The Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) Augmented Geosynchronous Laboratory Experiment (EAGLE) multi-mission spacecraft flight experiment was successfully launched on Air Force Space Command (AFSPC)–11 by a United Launch Alliance Atlas V rocket from Cape Canaveral, Florida, on April 14, 2018. ESPA is an AFRL innovative technology that increases the number of satellites that can be put into space on a single launch. Much like a train can just add extra cars to transport more cargo, one or more ESPA rings can be added under the primary payload to launch more satellites. EAGLE will demonstrate a maneuverable ESPA-based space vehicle design that allows six or more deployable or hosted spacecraft in geosynchronous orbit. It will also demonstrate the capability to provide low-cost access to geosynchronous orbit

and geosynchronous transfer orbit for smaller-class space vehicles by using excess weight and volume available on the EELV launch vehicle family. One of the EAGLE payload experiments is another AFRL-developed spacecraft called Mycroft, which is a separable, fly-away satellite. The Mycroft vehicle will deploy from EAGLE, drift to approximately 35 kilometers away, and cautiously progress over several months to ranges approaching 1 kilometer. While in orbit, the Mycroft spacecraft will be supporting the Mycroft program's three experimental objectives to advance Space Situational Awareness (SSA) technology in near-geosynchronous orbit. It will explore ways to enhance space object characterization and navigation capabilities, investigate control mechanisms used for flight safety, and explore the designs and data-processing methods for enhancing SSA. Other experiments hosted on EAGLE will detect, identify, and analyze system threats such as humanmade disturbances, space weather events, or collisions with small meteorites.

The University Nanosat Program (UNP) held the Nanosat-9 Phase-A downselect meeting in January 2018. The teams from the University of Colorado Boulder and the University of Georgia were selected to proceed to satellite build (Phase B). In addition, preparation for the tenth round of the University Nanosat Program (NS-10) are under way for a kickoff meeting in January 2019. Under NS-10, ten U.S. universities will be building small satellites and exploring SmallSat technologies, including propulsion, small-satellite laser communications, advanced radio-frequency communications, and rendezvous and formation flying, among others. Founded in 1999, the UNP was the first federally funded research program to fund small-satellite projects at universities. The objective of the UNP is to promote and sustain university research and education focused on small satellites and related technologies. The primary outcome of individual projects funded under this program has been the design, fabrication, and functional testing of a small satellite. Secondary objectives are to foster research in enabling technologies for small satellites and the design of experiments that can be performed by small satellites in orbit.

The Shiver mission includes four 12U CubeSats and is sponsored by the USAF Research Laboratory (AFRL). The Shiver mission is a formation-flying mission intended to study the practices, processes, and methods of formation entry and maintenance. Shiver will execute several formations and is testing autonomy on

the space vehicles by designing the vehicles to be able to maintain their own orbit. There are several flight-of-opportunity payloads for the formation mission as well. Shiver is scheduled to launch in late 2020.

Command and Control

Air Force

The Joint Space Operations Center (JSpOC) was redesignated as the Combined Space Operations Center (CSpOC) on July 18, 2018. The CSpOC Mission System (CMS) provides real-time, integrated Space Situational Awareness (SSA) to allow informed, rapid decision making by the Commander, Joint Functional Component Command–Space, including the ability to plan, direct, coordinate, and control operations of assigned forces. It will allow increased capability, including a User Defined Operational Picture (UDOP), a high-accuracy satellite positional database/catalog, increased capacity for additional space objects, ability to leverage nontraditional sensors/data sources, and automated satellite collision-avoidance assessment/prediction services.

The CMS Increment 2 is the program of record to replace the aging and sustainment-challenged Space Defense Operations Center, which met its design end of life in 2002. Increment 2 employs agile elements in a net-centric, service-oriented architecture (SOA) to allow

- capabilities to be incrementally deployed in service packs,
- loosely coupled capabilities/applications to enable the integration of the latest commercial and Government-developed software and technologies,
- operators to utilize a User Defined Operational Picture via Web start,
- third-party software deployment via a Software Development Kit, and
- the ability to tailor certain content of Service Pack(s) based on warfighter requirements and urgent needs.

The CMS Increment 2 Program Service Pack 9 is completing Operational Testing and Evaluation (OT&E). Service Pack 11 development is under way.

DOD has a need to improve both its systems' timeliness and accuracy and its processes for managing multiple simultaneous events to better enable commanders and decision makers to rapidly command and control (C2) space assets throughout the range of operations. Enterprise Space Battle Management Command

and Control (ESBMC2) is a command and control software (SW) program. The SW will be able to better integrate multiple streams of SSA, initial delivery of Indications and Warning (I&W), and counter-space data to provide decision makers with a clearer picture of the contested space environment. The program is specifically designed for the National Space Defense Center and aimed at managing any future space conflicts. ESBMC2 involves multiple lines of effort by the AFSPC, the Space and Missile Systems Center (SMC), AFRL, and the Air Force Rapid Capabilities Office (AFRCO) to quickly provide C2 capabilities across the DOD Enterprise and leverage commercial capabilities to the maximum extent possible. The ESBMC2 program will deliver an automated approach at multiple classification levels to link disparate information across geographically separated operations in order to direct forces on operationally relevant timelines. It will provide commanders and decision makers with the tools needed to improve timelines and accuracy in commanding and controlling space assets simultaneously. A Request for Information (RFI) for a Broad Agency Announcement (BAA) contract was issued in January 2017 and opened in May 2017. Responses have been received and will allow the ESBMC2 program to start developing initial space Battle Management Command and Control (BMC2) applications. Multiple Requests for Proposals (RFPs) will be going out based on RFI responses received. ESBMC2 lines of effort include the following:

- Providing the initial National Space Defense Center (NSDC) infrastructure (through 2019).
- Spiral 1: Initial delivery of I&W and Course of Action (COA) tools to the NSDC.
- Spiral 2: Infrastructure Initial Operational Capability (IOC), I&W, COA, sensor tasking using a satellite experiment effort, and multiple operation center collaboration.
- Spiral 3: Standup of the Shadow Operations Center (ShadowOC) for continued training and experimentation with prototypes, as well as improved Spiral 2 tools to meet top requirements.

The USAF Rapid Capabilities Office will develop enterprise open standards using a consortium and will leverage lessons learned. Spiral 4 will demonstrate space command and control using proven open, scalable, and interoperable

systems. The ESBMC2 program will also develop prototypes to address identified capability gaps at space operations centers.

Environmental Monitoring

Air Force

The development of the USAF's family of systems to meet future Space Based Environmental Monitoring (SBEM) sensing needs progressed significantly in 2018. All elements of the family of systems are on track to replace legacy sensing capabilities in the early half of the next decade.

The Weather Satellite 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 provide some residual operational capability. 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 spring 2019 and initial launch capability in late 2022. Technical risk for WSF-M development is being reduced via the Operationally Responsive Space-6 (ORS-6) mission. The ORS-6 technology demonstration incorporates lessons learned from the NASA Jet Propulsion Laboratory (JPL) COWVR payload development and includes a potential flight aboard the International Space Station.

The Electro-optical/infrared Weather System (EWS) pre-acquisition activities were conducted throughout the year leading to the release of the system Request for Proposals in late 2018. EWS will satisfy DOD's two highest-priority SBEM sensing needs from the family of systems' "early-morning" orbit—Cloud Characterization and Theater Weather Imagery. Initial launch capability for EWS is predicted for late 2023. Additionally, to reduce the risk of coverage gaps between the fly-out of legacy DMSP and the availability of EWS, the USAF is developing the Operationally Responsive Space-8 (ORS-8) mission. ORS-8 was initiated in

response to a United States Strategic Command (USSTRATCOM) urgent need and is on track for initial launch capability in 2021.

Throughout 2018, the USAF and the National Oceanic and Atmospheric Administration (NOAA) conducted various technical interchanges, site surveys, and planning activities for the 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 United States geostationary SBEM satellite. 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.

Missile Warning/Attack Assessment

Air Force

The Space Based Infrared System (SBIRS) remains an unblinking eye for ballistic missile warning and defense, battlespace awareness, and technical intelligence for the United States and its allies. SBIRS satellites and ground systems provide operational capability today and will continue to incrementally deliver additional capability to the warfighter in the future. The USAF is taking projected threats seriously and focusing investments on maturing resilient technology now. An acquisition strategy is under development for a next-generation Overhead Persistent Infrared (OPIR) space segment. The strategy is being discussed in predecisional forums within the USAF and seeks to replenish the constellation and address emerging resiliency requirements while addressing a rapidly changing threat environment.

Positioning, Navigation, and Timing

Air Force

The Global Positioning System (GPS) program celebrated its 23rd 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 four billion worldwide. The first GPS III satellite is scheduled for launch on December 2018. The second GPS III satellite completed assembly and factory testing in August 2018 and is in storage awaiting shipment to the launch base. GPS III satellites 3 through 10 are in various stages of production. In addition, the GPS III Follow-on (GPS IIIF) contract was awarded in September 2018. GPS IIIF satellites will provide an eightfold increase in anti-jam performance over current GPS satellites. The GPS Next-Generation Operational Control System (OCX) achieved its Milestone B recertification in September 2018. This modernized ground system will enable the effective use of the latest military and civilian GPS signals. For military GPS user equipment, the first M-Code ground receiver card obtained security certification and completed qualification tests in 2018. These military GPS receiver cards will 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) 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. Three on-orbit AEHF satellites augment the existing Milstar constellation, providing protected satellite communications for strategic users. Three additional AEHF satellites are currently in production, with the next launch forecast to occur in the first quarter of FY 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 April 18, 2018, FAB-T received Milestone Decision Authority approval to purchase the new ground transportable antenna configuration. In total, 51 Low Rate Initial Production terminals are now on contract and ten terminals have been installed.

The Enhanced Polar System (EPS) program now has two hosted payloads on orbit that were launched in FY 2015 and FY 2017. Operational testing is slated for

FY 2019, along with initial operational capability shortly thereafter. The EPS will replace the Interim Polar System to ensure that critical protected communications requirements above 65 degrees north latitude are satisfied for joint forces. The USAF is procuring two replenishment EPS payloads to prevent a Military Satellite Communications Systems Directorate (MILSATCOM) mission gap in the polar region in the 2023 timeframe. A sole-source Request for Proposal for two functional equivalent EPS payloads was released to Northrop Grumman Aerospace Systems in November 2017 and was definitized on August 10, 2018.

The Wideband Global Satellite Communications (WGS) satellite program consists of ten satellites with nine currently on orbit. WGS 10 is scheduled to launch in 2019. The Consolidated Appropriations Act of FY 2018 includes a $600 million congressional addition to "fully fund" WGS 11–12. The USAF released, on June 21, 2018, a sole-source Request for Proposal to Boeing for two WGS satellites. 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 up to 3.6 gigabits per second (Gbps) per satellite (13.7 Gbps worldwide as of April 2016) to support various missions of the Unified Combatant Commanders, military services, other DOD agencies, and international partners (Australia, Canada, Denmark, the Netherlands, New Zealand, and Luxembourg).

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 Protected Tactical Enterprise Service (PTES) is a ground system that will provide anti-jam protection via WGS to tactical warfighters currently unable to operate through interference in anti-access/area-denial operational environments. The development contract Request for Proposal was released on March 29, 2018, and is currently in source selection. On June 18, 2018, the USAF Acquisition Executive designated PTES as an FY 2016 National Defense Authorization Act (NDAA), Section 804, Rapid Prototyping activity and authorized PTES to pursue a prototype capability (two Navy Carrier Strike Groups in the Pacific Theater) by the end of the first quarter of FY 2022.

Space Access

Air Force

The Evolved Expendable Launch Vehicle (EELV) program continued to successfully place satellites into orbit during FY 2018. United Launch Alliance (ULA) continued its record of 100 percent mission success with four National Security Space (NSS) launches during FY 2018:

(Launch Date, Launch Vehicle Configuration, Payload)

- October 15, 2017, Atlas V (421), National Reconnaissance Office Launch (NROL)-52
- January 12, 2018, Delta IV Medium+ (5,2), NROL-47
- January 19, 2018, Atlas V (411), SBIRS Geostationary (GEO) 3—Flt 4
- April 14, 2018, Atlas V (551), AFSPC-11

In the next fiscal year, EELV will be retitled the National Security Space Launch program in accordance with congressional direction contained in the FY 2019 National Defense Authorizations Act, enacted August 13, 2018.

The Launch and Test Range System (LTRS) provides public safety and assured access to space. LTRS modernization efforts continue at both the Eastern and Western Ranges, Patrick AFB/Cape Canaveral AFS, Florida, and Vandenberg AFB, California, respectively, in support of DOD, civil, and commercial satellite launches and DOD ballistic missile evaluation launches. LTRS comprises numerous subsystem capabilities: Range Safety and Command Destruct, Radar and Optics Tracking, Telemetry Reception, Communications and Data Handling, Timing and Sequencing, and Planning and Scheduling.

The USAF continued to competitively award launch services in FY 2018. The GPS III-4, -5, and -6 launch services awards were made on March 14, 2018, to SpaceX, while AFSPC-8 and AFSPC-12 launch services awards were made on March 14, 2018, to ULA. Additionally, AFSPC-52 launch service was competitively awarded to SpaceX on June 20, 2018, and is scheduled to be launched on the Falcon Heavy. The USAF's program office released RFP 1A-6 on January 31, 2018. RFP 1A-6 includes six launch services (AFSPC-44, SBIRS GEO-5, SBIRS GEO-6, Silent Barker, NROL-85, and NROL-87) that will be awarded individually. Proposals were received on April 16, 2018, with awards projected in the first quarter of FY 2019.

The USAF funded three providers to develop full launch systems through launch service agreements (LSAs) in 2018 and ultimately select two providers for the next generation of launch service procurements in late 2019. These LSAs remain a key component in moving away from the use of non-allied space launch engines, maintaining assured access to space with two or more fleets of launch vehicles, and introducing sustainable competition for future EELV NSS launch services to maintain a healthy space industrial base with more-affordable pricing.

Range modernization efforts continued in FY 2018 with the following accomplishments:

- The Western-Range Modernization of Network (WMN) contract was awarded as a small business set-aside to upgrade the Western Range mission communications core, addressing obsolescence issues and improving cyber protection. As part of WMN, the contract upgrades the Western Range's communications network from Asynchronous Transfer Mode to Internet Protocol version 6 (IPv6).
- Construction was completed on a new Range Communications Facility (RCF) at the Eastern Range, and equipment installation has already commenced. The purpose of the new building is to relocate communications capabilities from the XY building to a new RCF, resolving building deterioration, a high risk of flooding, software code noncompliance, and other high-risk capability off-loading. The expected completion date is November 2023 (FY 2024).
- Modernization of the Range Command Destruct subsystem continues, in order to employ a new secure command destruct code and the enhanced flight termination system, the latter mandated by the National Security Agency.
- Autonomous Flight Safety System (AFSS) implementation is ongoing. AFSS will transfer the most critical range and public safety requirements to rocket and test vehicle onboard systems, enabling agile acquisition of commercial off-the-shelf solutions for instrumentation needs.
- Modernization of LTRS capabilities ensures that both ranges are better able to sustain operations and respond more readily to a changing space threat environment, enabling the facilities to rapidly integrate new

capabilities to make the ranges a more resilient warfighting force in a contested battlespace.

In 2017, with changes in 2018, Congress redesignated the Operationally Responsive Office as the Space Rapid Capabilities Office (Space RCO) within USAF Space Command as a program office. The mission of the Space RCO is 1) to contribute to the development of low-cost, rapid-reaction payloads, busses, launch, and launch control capabilities in order to fulfill joint military operational requirements for on-demand space support and reconstitution; 2) to coordinate and execute space rapid capabilities efforts across the Department of Defense with respect to planning, acquisition, and operations; and 3) to rapidly develop and field new classified space capabilities. This mission enables the ability to expedite the fielding of critical space capabilities to the warfighter and to enhance the materiel responses to Combatant Commander needs.

On May 31, 2018, ORS-5 was declared operational to meet validated urgent needs. A Space Situational Awareness payload successfully launched in August 2017, ORS-5 accomplishes roughly 85 percent of the work of its predecessor, Space Based Space Surveillance Block 10, freeing it to focus on higher priorities.

ORS-7 has demonstrated the ORS responsive manufacturing assembly line by producing two CubeSats for the Coast Guard's Arctic search-and-rescue mission. These two ORS-7 CubeSats have completed final integration and testing and will be integrated into the Department of Homeland Security's Adaptive Space-based Analytics Project when launched in November 2018.

ORS-8 continues its development to satisfy the Department of Defense–validated urgent need for an interim capability for weather Gap 1 (cloud characterization) and Gap 2 (theater weather imagery) with a planned launch in 2021.

On June 7, 2018, the Space RCO Executive Committee approved a new program, ORS-9, to address the U.S. Strategic Command–validated urgent need for persistent all-weather tactical intelligence, surveillance, and reconnaissance.

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 in ways that include command and control, early warning, and propaganda dissemination. Development was continued in 2018 for the purchase of seven new Counter Communications Systems for the Air National Guard. The preplanned product improvements, which transition the system to Increment 10.2, are on track and progressing well. Nine of 16 systems have been delivered to date, with remaining deliveries scheduled by the end of FY 2020.

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 2018, 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 the 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 SSA 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

The 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 installation and checkout at the operations center is complete, and the construction of the sensor site is near completion. In addition, the radar hardware and software production are near completion. Installation and checkout of the radar components are under way at the sensor site. The program is on track to achieve IOC in the first quarter of FY 2019.

The Geosynchronous Space Situational Awareness Program (GSSAP) vehicles will operate in the near-GEO regime and provide the United States with an operational capability to support U.S. Strategic Command's Space Surveillance Operations as a dedicated space-based SSN sensor. The enhanced maneuverability of GSSAP also allows rendezvous and proximity operations to enable on-orbit object characterization and anomaly resolution. Two additional GSSAP space vehicles were launched in August 2016.

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.

NextGen is essential to protecting aviation's contributions to U.S. economic strength. A healthy aviation industry is vital to the Nation's prosperity, as civil aviation contributes 10.6 million jobs and $1.6 trillion a year to the U.S. economy. In total, the FAA estimates that NextGen implementations from 2010 through 2018 have accrued $6 billion in early benefits to industry and society.

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 and is operational at 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 ADS-B—which is fully integrated—and Data Communications (Data Comm), which supplements

voice communications with digital text-based messages between controllers and pilots.

Data Comm

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 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 automatically 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 to implement en route services that support the portion of flight at cruising altitudes. 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. En Route Data Comm capabilities are currently being field tested at the first two Air Route Traffic Control Centers. 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

Aircraft flying in most controlled airspace must be equipped to transmit their position using ADS-B Out by January 1, 2020. The Equip 2020 Government-industry working group is trying to eliminate equipage impediments for commercial and general aviation operators. As of October 2019, more than 93,000 U.S. aircraft are equipped with properly functioning ADS-B Out avionics.

ADS-B uses GPS to determine aircraft position more accurately and with faster updates than radar. 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 a $500 rebate in September 2016 to operators of U.S.-registered fixed-wing single-engine piston aircraft. The rebate is intended to defray ADS-B equipment and installation costs. More than 10,200 pilots claimed the offer that ended one year after its start. On October 12, 2018, the FAA restarted the rebate program. It will run for one year or until funds are exhausted. As of September 30, 2019, the program manager recorded

- 9,792 reservations;
- 8,640 fly-outs to fly, test, and validate equipment; and
- 8.482 rebate payouts by the FAA.

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 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 89 remote sites located at other FAA, military, and civilian 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 at 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

Besides the NAC, the FAA promotes the acceptance and adoption of NextGen technologies and procedures through cooperation with industry and Federal partner agencies.

Made up of senior executives from NextGen Federal partner agencies, the NextGen Executive Board is one of two bodies that guide interagency NextGen activities. 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.

The NextGen Executive Weather Panel allows the FAA, NASA, and the departments of Defense and Commerce to collaborate on weather-related research and development, policy, and implementation activities.

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 operations in U.S. airspace in August 2016, nearly 400,000 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 in which the FAA supplies 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 for 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 over 100,000 authorization requests, and it 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 how the FAA manages airspace. 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, and 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's Air Traffic Organization is leading the development of 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 2018, the Department of Commerce (DOC) took significant steps to advance the U.S. commercial space industry while continuing its important role as a leading civilian operational space agency.

In January 2018, Secretary of Commerce Wilbur Ross identified space commerce as his top priority for DOC in his strategic plan for 2018–22. The plan includes guidance for DOC to expand and elevate the Office of Space Commerce, to actively participate in the National Space Council in advancing American leadership in commercial space activities, and to support American companies operating in space.

Consistent with this guidance, Secretary Ross attended all three FY 2018 meetings of the National Space Council, submitted a package of regulatory reform recommendations to the Council Chairman, and began completing multiple tasks issued by President Donald Trump in Space Policy Directives (SPD) 2 and 3. SPD-2 directs DOC to review and revise its remote sensing regulations; consolidate DOC's regulation of commercial spaceflight activities within the Office of the Secretary; provide a report on improving the global competitiveness of the U.S. space sector through spectrum policies, regulation, and activities at the International Telecommunications Union; and participate in a review of export licensing regulations affecting commercial spaceflight activity. SPD-3 designates DOC as the lead civil agency for the provision of Space Situational Awareness (SSA) data and Space Traffic Management (STM) services; it directs DOC to lead or participate in seven lines of effort related to SSA and STM.

To implement its SPD-2 tasks, DOC submitted a proposal to Congress in May 2018 to consolidate and elevate the Office of Space Commerce and the

Commercial Remote Sensing Regulatory Affairs (CRSRA) Office into the Office of the Secretary. DOC further transmitted to Congress a legislative proposal that would permanently elevate the Office of Space Commerce to a bureau that would provide mission authorization to proposed commercial space activities. In June 2018, CRSRA published an Advance Notice of Proposed Rulemaking on the licensing of private remote sensing systems and collected public comments in preparation for a Notice of Proposed Rulemaking to be issued in early FY 2019. DOC also prepared recommendations on space export control reform for interagency consideration and will release a Notice of Inquiry soliciting further industry input for future regulatory changes.

To implement its SPD-3 tasks, DOC engaged with DOD, the Department of Transportation (DOT), NASA, and other interagency partners to gain a full understanding of the existing SSA/STM processes and develop a plan for transitioning the customer service interface for commercial space users from DOD to DOC over the coming years. DOD transmitted the transition plan to the National Space Council and continues to work with DOC in executing other SPD-3 tasks.

In March 2018, DOC supported the public release of the National Space Strategy, which DOC had helped formulate during FY 2017. The Strategy puts forward a reinvigorated, whole-of-Government approach to ensuring U.S. leadership and success in space. Among other things, the Strategy prioritizes regulatory reforms to unshackle American industry and ensure that the United States remains the leading global provider of space services and technology.

In November 2017, DOC's Office of Space Commerce and the FAA Office of Commercial Space Transportation published the second edition of their *Introduction to U.S. Export Controls for the Commercial Space Industry*. The guidebook provides basic information to help commercial space organizations, especially emerging entrepreneurial firms, considering business in the international market.

During FY 2018, the National Oceanic and Atmospheric Administration (NOAA) continued to support the development of a commercial market for satellite-based weather data. In September 2018, NOAA announced radio occultation data buys from three commercial satellite firms under Round 2 of its Commercial Weather Data Pilot (CWDP). NOAA will use CWDP Round 2 to evaluate the impact of the commercial data on NOAA's numerical weather prediction models

that will further support the demonstration of radio occultation data; NOAA will also develop internal infrastructure needed to pursue the procurement of commercial radio occultation data operationally.

During FY 2018, DOC 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 senior body that advises and coordinates Federal agencies on GPS matters. DOC's Office of Space Commerce continued to host the physical offices of the committee as well as the *https://www.gps.gov* Web site, which remained the leading source of online information about GPS.

During FY 2018, DOC participated in various dialogues on satellite navigation and space cooperation with Europe and individual nations, including Japan, the United Kingdom, Canada, and China. The Office of Space Commerce convened a meeting with the European Union (EU) to discuss U.S. industry concerns about EU regulations and access to technical information on Galileo, the EU satellite navigation system. The Office of Space Commerce also participated in continued negotiations with the EU on possible U.S. access to Galileo's Public Regulated Service.

NOAA's Geostationary Operational Environmental Satellites, known as the GOES-R Series, provide 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. The currently operational GOES satellites (GOES-15 and GOES-16) continuously monitor the Western Hemisphere by circling Earth in a geosynchronous orbit 22,000 miles above the equator, meaning they remain over one position on Earth by orbiting at a speed matching Earth's rotation. GOES imagery and data provide meteorologists with information to forecast weather in the short term, track severe storms, and estimate precipitation levels for issuing possible winter storm warnings and spring snow-melt advisories.

In FY 2018, the second satellite of the GOES-R series, GOES-17 (formerly GOES-S), successfully launched at 5:02 p.m. eastern time on March 1, 2018. Once it becomes operational (expected by December 2018), GOES-17 will become GOES West and will capture real-time imagery of Earth's Western Hemisphere, from the West Coast of the United States all the way across the Pacific Ocean to New

Zealand. Together, GOES-17 and GOES-16, the first satellite in the GOES-R series, will continue 40 years of GOES coverage. These satellites are more advanced than any other weather satellite of their kind and provide more detailed and accurate data for forecasters.

National Oceanic and Atmospheric Administration

In FY 2018, the National Oceanic and Atmospheric Administration's (NOAA) satellites remained as critical as ever, monitoring the wildfires in the western United States and Canada; hurricanes in the Gulf of Mexico, 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 and data used in preparation for events impacting our weather, oceans, and climate. NOAA manages and operates four primary types of environmental satellites: geostationary environmental satellites, polar-orbiting environmental satellites, ocean altimetry satellites, and a deep space satellite for space weather monitoring and forecasting.

Polar-Orbiting Satellites

On May 30, 2018, the first satellite in NOAA's Joint Polar Satellite System (JPSS) passed rigorous testing and became operational. Launched on November 18, 2017, as JPSS-1 and designated as NOAA-20 once it reached orbit, the satellite features the latest and best technology NOAA has ever flown in a polar orbit to capture more precise observations of the world's atmosphere, land, and waters. Data collected by the satellite's advanced instruments (which can be found at *https://www.jpss.noaa.gov/mission_and_instruments.html*) helps to improve the accuracy of three- to seven-day forecasts.

NOAA's primary polar-orbiting environmental satellites, NOAA-20 and Suomi National Polar-orbiting Partnership (Suomi NPP), orbit Earth at an altitude of approximately 517 miles, passing close to both poles and providing complete views of weather around the world. NOAA-20 provides 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. The project is a partnership between the National Space Organization (NSPO) of Taiwan and the United States. Over its lifetime, COSMIC has proven to be an extremely cost-effective way to gather an abundance of atmospheric data, including three-dimensional profiles of temperature, humidity, and pressure. Due to the success of the COSMIC program, the follow-on advanced COSMIC-2/FORMOSAT-7 mission is being developed between the American Institute in Taiwan (AIT) and the Taipei Economic and Cultural Representative Office in the United States (TECRO), for which NOAA is AIT's designated representative and NSPO is TECRO's designated representative. During 2018, the teams continued preparing the six COSMIC-2/FORMOSAT-7 satellites for launch into an equatorial orbit as part of the U.S. Air Force Space Test Program 2 (STP-2) mission in 2019. The NOAA ground system is ready to support data acquisition. Processing the advanced technology of COSMIC-2/FORMOSAT-7 is expected to improve forecasts of tropical winds.

Ocean Altimetry Satellite

Jason-3, an international satellite mission jointly led by NOAA, the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), NASA, and the French space agency (Centre National d'Études Spatiales [CNES]), is the fourth in a series of U.S.-European satellite altimeter missions designed to measure the sea surface height variability of the global ocean. Initially, the satellite flew in tandem with its predecessor, Jason-2, 830 miles above Earth's surface, collecting comparable measurements of sea surface height down to the subcentimeter level. Then, in mid-October 2016, Jason-2 was moved so that its ground track now "interleaves" with that of Jason-3. The result is a doubling of the Jason satellites'

observations of the ocean. Now, with twice the coverage, the Jason mission is providing more accurate coverage of ocean conditions and will improve the intensity forecasts during this year's Atlantic hurricane season.

In June 2018, Jason-2 marked its tenth year in orbit. The satellite has completed just over 47,000 trips around Earth since it was launched into space on June 20, 2010. Originally designed for a three- to five-year mission, the Jason-2 satellite has now spent a decade collecting valuable information about Earth's oceans, such as mapping the ocean floor and providing scientists with observations to study global climate phenomena like El Niño and La Niña (see information at *https://oceanservice.noaa.gov/facts/ninonina.html*), as well as monitoring the long-term rise in global sea level. In July 2017, Jason-2 began a new science mission when it was maneuvered into a slightly lower orbit. Jason-2 began measuring the height of the sea surface, wave heights, and ocean wind speeds along a series of very closely spaced ground tracks (just five miles apart). Scientists are using these new sea surface measurements to improve maps of the shape and depth of the ocean floor. Only about 15 percent of the world's ocean depths have been directly measured at a high resolution (100 meters or more), while 50 percent of the world's coastal waters remain completely unsurveyed. The data collected during these mapping missions have several societal and strategic benefits. For example, real-time information about ocean currents is important for marine, fishing, and naval operations. In addition, accurate measurements of ocean heat content can help weather forecasters better predict the intensity of hurricanes and tropical storms and improve global climate forecasts.

Space Weather Satellites

Launched in February 2015, 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. Without timely and accurate warnings, space weather events, like the geomagnetic storms caused by changes in solar wind, have the potential to disrupt nearly every major public infrastructure system,

including power grids, telecommunications, aviation, and GPS. DSCOVR succeeded NASA's Advanced Composition Explorer's (ACE) role in supporting solar wind alerts and warnings from the L1 orbit, the neutral gravity point between Earth and the Sun approximately one million miles from Earth. NOAA's Space Weather Follow On (SWFO) program is exploring options to ensure the continuity of space weather observations beyond the current generation of missions. In 2017, NOAA started developing a flight compact coronagraph (CCOR) to continue to obtain Coronal Mass Ejection (CME) imagery, which is required to forecast space weather warnings.

Additional Space-Based Capabilities

NOAA, together with international partners, flew two other types of instruments on some of its satellites. Argos is a data collection and location relay system administered under an agreement between NOAA and CNES initiated in 1974. CNES provides sensors that collect a wide variety of in situ measurements, including data on atmospheric pressure, sea temperature, ocean-current velocity, animal migration patterns, and river water levels. The Search and Rescue Satellite-Aided Tracking system (COSPAS-SARSAT) is an international system that uses satellites to locate emergency beacons carried by ships, aircraft, or individuals and communicate location information to search-and-rescue authorities. NOAA provides space on its polar-orbiting satellites for the French processor and Canadian receiver. The system has rescued over 43,000 people worldwide since 1982. The total number of SARSAT rescues in FY 2018 was 334.

Another capability lies in NOAA's partnership with the Japan Aerospace Exploration Agency (JAXA) on the Advanced Microwave Scanning Radiometer (AMSR). The AMSR2 onboard the JAXA Global Change Observation Mission–Water (GCOM-W) satellite is a remote sensing instrument for measuring weak microwave emission from the surface and the atmosphere of Earth. NOAA provides ground data acquisition for GCOM-W in exchange for access to AMSR2 data. From about 700 kilometers above Earth, AMSR2 provides us with highly accurate measurements of the intensity of microwave emission and scattering. The antenna of AMSR2 rotates once per 1.5 seconds and obtains data over a 1,450-kilometer

swath. This conical scan mechanism enables AMSR2 to acquire a set of daytime and nighttime data with more than 99 percent coverage of Earth every two days.

International Activities

In 2018, NOAA continued to work with users of NOAA's GOES satellite data in North, Central, and South America to ensure a smooth transition to the new generation of ground receiving stations—the GOES Rebroadcast (GRB) stations—and to promote the use of GEONETCast Americas (GNC-A), a cost-effective satellite-based dissemination system. NOAA coordinated trainings in North, Central, and South America and the Caribbean on the use of data from the GOES-R series satellites. NOAA continued to strengthen collaboration with Europe, signing an updated Copernicus Technical Operating Arrangement with the European Space Agency to include cooperation on Sentinel-5P Loose Flying Formation, and signing a Framework Science Cooperation Agreement with EUMETSAT.

National Institute of Standards and Technology

In FY 2018, 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 2018, 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, and time, as well as their derived units (force, acceleration, sound pressure, and ultrasonic power). For instance, NIST provided calibrations of length standards for U.S. aerospace companies to ensure that the dimensions of their manufactured parts conformed to design specifications. Separate load cell calibrations 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.

In developing metrology to support advanced manufacturing, NIST worked with DOD, Boeing, Lockheed Martin, and others on methods to quantify the performance of laser scanning, a key new technology for advanced manufacturing that offers potential cost savings, increased measurement throughput, and high data densities. The technology is especially suited for the manufacture of large structures such as aircraft components. In December 2017, ASTM published a documentary standard for the performance evaluation of laser scanners, led by NIST and supported by leading manufacturers of laser scanners, such as FARO, Surphaser, Leica, Trimble, and Riegl.

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 weld ability 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. In FY 2018, NIST partnered with Government agencies such as NASA, the FAA, and DOD to help overcome challenges in the qualification and certification of AM materials, processes, and parts. For instance, NIST collaborated with members of the Additive Manufacturing Consortium (AMC) to conduct round-robin testing and determine the mechanical properties of parts made from the Inconel 625 aerospace alloy. 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 continued to provide leadership and contributions to support the widespread adoption of AM processes. Specific events included the following:

- In June 2018, NIST hosted the AMBench Conference (*https://www.nist.gov/ambench*), the first in a series of meetings on the creation of benchmarks for additive manufacturing and the validation and verification of process, microstructure, and property models, thereby improving the quality and consistency of additive processed parts and enabling qualification and certification of these parts for aerospace applications.
- NIST attended the FAA-sponsored workshop and training on the methodology and related software for probabilistic fracture mechanics (PFM) held in San Antonio, Texas, in March 2018 for potential application to analysis of high-criticality additive manufacturing parts used by the aerospace industry.
- NIST participated in the Advisory Council for Aviation Research and innovation in Europe (ACARE) meeting at the FAA to explore areas of collaboration between EU and U.S. aviation industries.

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. For instance, NIST continued efforts to support the development of model-based representations for use across aerospace manufacturing and business enterprises. These efforts include

hosting the annual Model-Based Enterprise Summit, garnering the largest participation to date, and playing a leading role in the late-2017 draft publication of ASME Y14.46 Product Definition for Additive Manufacturing.

Much of NIST's support for the aerospace supply chain came with interactions through the suppliers themselves. In the first three quarters of FY 2018, the Hollings Manufacturing Extension Partnership (MEP) National Network engaged in 206 projects with 131 individual manufacturing clients designated with an aerospace North American Industry Classification System number (NAICS 3364). The MEP post-project, follow-up survey of aerospace NAICS companies revealed that MEP services resulted in the creation or retention of 4,166 aerospace jobs, over $76 million in new sales, over $201 million in retained sales, over $44 million in new investment, and over $60 million in cost savings.

Table 1. NIST MEP Aerospace Impact.

Total Sales	$278,195,505.00
Total Cost Savings	$60,441,013.00
Total Investment (Policy and Procedures [P&P], Physical and Environmental [P&E], Information Technology [IT], Workforce, Other)	$44,558,346.00
Total Jobs	4,166

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 FY 2018, NIST also served on a National Academies committee responsible for a report on Microbiomes of the Built Environment, an effort cosponsored by NASA.

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 the space solar cell manufacturer Hamadani. 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.

NIST, members of the aerospace field (Thermacore, Marshall Space Flight Center, and the Air Force Academy), and members of academia (the University of Tennessee, the University of Missouri, and Michigan Technology University) used the NIST neutron facility resources to perform unique measurements on several aerospace-related systems, including the following:

- Performed thermal measurements on a working, prototype lithium-cooled niobium heat pipe that cools the leading edge of hypersonic aircraft.
- Tested for foreign object debris (FOD) in a relief valve that is an intrinsic component of spacesuits used by International Space Station (ISS) crewmembers, ensuring safe operation of the valve.
- Studied the water distribution in fuel-cell flow fields and gas diffusion layers.
- 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.

Airspeed, hydrocarbon liquid flow, and gas flow measurements 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 aerospace industry and DOD customers, supporting both laser weapons systems and target designation systems. NIST's Missile Defense Transfer Radiometer (MDXR) performed measurements for several space simulation chambers at Raytheon Missile Systems, Inc., and at the Johns Hopkins University Applied Physics Laboratory for the calibration of infrared remote sensing systems for the Missile Defense Agency.

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 2018, NIST collaborated with NASA 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 improve small arrays of SNSPDs to increase the device area, an important development for future usage in laser communication systems. Additional efforts by NIST and JPL to improve SNSPDs included optimizing ultraviolet light detection and exploring the use of a new material in SNSPD development.

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 a low-power, hybrid fiber/waveguide comb design to Honeywell and to Vescent Photonics 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 participated in the 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 intercomparisons of ground clocks. In support of these efforts, NIST researched, developed and evaluated an ytterbium (Yb) optical lattice clock as a candidate for the Space Optical

Clock program and reached previously unachieved levels of certainty and reproducibility. NIST also finished its research, development, and evaluation of a highly miniaturized femtosecond laser frequency comb for potential future applications in the Space Optical Clock program. NIST research pushed the state of the art significantly, and the high-performance optical microcomb could be used in space for direct comparisons of optical and microwave clocks, for referencing microwave time and frequency signals directly to optical standards, and other applications.

Calibrations and Sensor Development for Satellites

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

NIST continued to develop and characterize measurement methods for advanced optics used in aerospace and space applications, essential components of air- and space-borne imaging systems and telescopes. In collaboration with NASA, NIST developed a new mirror-based method to assess the capabilities of inspection equipment used to measure fine surface features on optical surfaces. Furthermore, NIST collaborated with NASA to develop a new method to measure the form errors of mandrels used in the fabrication of x-ray mirrors. The new method, based on computer-generated holograms, has the potential to meet currently unattainable metrology requirements for the next generation of x-ray mirrors for future space-borne x-ray telescopes. NIST continued to work with researchers from the University of Texas at Austin on a NASA-funded project to improve the performance of space-based and ground-based spectrometers used in the analysis of remote stars, interstellar gases, and extrasolar planets.

NASA's next-generation suborbital and satellite observatories require new detectors with improved sensitivity and scalability. With NASA funding, NIST developed 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, LiteBIRD, and other next-generation satellites. These sensor technologies offer new capabilities for the detection of electromagnetic signals, from millimeter waves like the cosmic

microwave background (CMB) through x-rays, and can help research aspects of star formation. Improvements to TES technology enabled a number of new ground-based instruments, including a large x-ray spectrometer to be sited at Linac Coherent Light Source (LCLS)–2 and the very large CMB detector arrays for 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 at institutions working on NASA-funded projects (California Polytechnic Institute; Stanford University; Massachusetts Institute of Technology; 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, for process control, and to qualify instrumentation for flight and space travel. NIST provided calibration support to NASA Langley Research Center and the Harris Corporation for the Cross-track Infrared Sounder (CrIS) that is part of the NASA/NOAA Joint Polar Satellite System (JPSS). 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.

NASA and NOAA contractors heavily used NIST's SURF III in FY 2018, amassing over 700 hours of beam usage. Calibrations enabled by SURF III helped to maintain the accuracy of the instrumentation for the EUV Variability Experiment (EVE) aboard NASA's Solar Dynamics Observatory; the EUV and X-ray Irradiance Sensor (EXIS) for NOAA's GOES-S, T, and U satellite missions; and the Miniature X-ray Solar Spectrometer (MinXSS) nanosatellite. These instruments are used to study soft x-ray and EUV solar irradiance and its variability. The NASA EVE measurements are important for tracking the solar storms that impact space-based communications and navigation technologies, and the NOAA EXIS measurements provide NOAA with data important to climate modeling.

In support of research of Earth's surface and atmosphere, NIST continued its collaboration with NOAA on the calibration of the Marine Optical BuoY (MOBY) used in the calibration of ocean-color measurements provided by satellite sensors. NIST's participation in the MOBY Refresh effort will help reduce overall measurement uncertainties and allow the current system to be retired. In FY 2018, NIST also assisted JPL in developing calibration procedures for the Orbiting Carbon Observatory III, equipment installed on the ISS to observe the complex dynamics of Earth's atmospheric carbon cycle.

NIST collaborated with the University of Colorado Laboratory for Atmospheric and Space Physics (LASP) and NASA's Earth Science Technology Office to develop and fabricate a Carbon Nano-tube Electrical Substitution Radiometer (CNT ESR) for the Compact Solar Irradiance Monitor (CSIM) instrument, able to measure solar power that serves as a baseline for climate change measurements. The collaboration also developed and fabricated the Carbon Absolute Electrical Substitution Radiometer (CAESR). Mounted on a NASA CubeSat platform, CAESR is able to perform absolute measurements of total broadband solar power to support climate change monitoring. The teams extended the technologies used in the CSIM and CAESR 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 from which measurements were made.

NIST designed and assembled three standards, based on carbon nanotubes, for NASA JPL to support their development and calibration of a water-ice sensor designed to survey various bodies in the solar system with reduced measurement uncertainty. 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 worked with Johns Hopkins University and NASA to measure the optical constants (n and k) of iron and nickel, fundamental parameters that govern the reflectance (and transmission) of light from a material. Iron metal is a key component of many planetary surfaces and can be used to measure the effects of space weathering (which includes solar wind sputtering and micrometeoroid impact melting and vaporization).

NIST, in partnership with NASA and the University of Maryland Baltimore County, 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, with the goal of enabling the Moon to serve as a calibration source for satellite sensors in space. The team integrated a specialized instrument, Air–LUnar Spectral Irradiance (LUSI), into a wing-pod of the ER-2 aircraft to track the Moon and measure lunar irradiance during flight.

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 2018, NIST provided results for atomic carbon, copper, vanadium, lanthanum, cerium, and other elements of particularly strong current interest and disseminated them publicly through a new release of its online Atomic Spectra Database, v.5.5 (*http://physics.nist.gov/asd*). NIST also developed and released a new interface for Laser Induced Breakdown Spectroscopy (LIBS) that is used, for instance, on the Mars rover Curiosity.

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 worked to develop 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 completed, delivered, and installed 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 is now being used for exoplanet searches around M-dwarfs (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 who 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, and 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 specific 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). Following consultation with ATCA's president and chief executive officer (CEO), ITA organized a panel on U.S. Government (USG) Trade Facilitation Services for ATCA's 2018 Annual Conference and Exhibition in National Harbor, Maryland.

OTM participates in multiple fora 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 USG. 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 USG. OTM also represents ITA on the Unmanned Aircraft Systems Standards Collaborative (UASSC) hosted by the American National Standards Institute (ANSI). The UASSC coordinates 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 in order to foster the growth of the UAS market worldwide.

Throughout the year, OTM organized and led four meetings of ITAC 1. The committee provides advice to the Secretary of Commerce and U.S. Trade

Representative on aerospace-related trade policy issues. This year, the Committee provided an advisory opinion to the Secretary of Commerce and the U.S. Trade Representative with respect to negotiating objectives for the U.S.-Mexico free trade agreement and decisional draft statutory report on NAFTA and the trade agreement with Mexico.

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.

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 is scheduled for review in 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. As a member of the U.S. delegation, ITA helped ensure that the interests of industry were addressed as the 2011 ASU was negotiated, continues to monitor implementation, and will participate in any review. In FY 2018, ITA helped draft a successful U.S. proposal that enabled EXIM to provide enhanced financing support to a small U.S. manufacturer for its export of small agricultural aircraft. ITA also closely monitored conditions in the aircraft finance market and provided advice on the importance of restoring EXIM to full functionality 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. In order 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 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 2018, ITA's Advocacy Center had 400 active cases in the aerospace and defense sector. In total, the project value of those active cases equaled approximately $336.5 billion with $319.7 billion in expected U.S. export content. During FY 2018, the Advocacy Center had 32 wins in the aerospace and defense sector. Of those wins, 13 were in the aviation sector, 11 were in the defense equipment sector, and four were in the space sector. The total project value of those wins equaled $40 billion, with approximately $34.3 billion in U.S. export content.

In July 2018, ITA organized and supported the Commerce Department's participation in the Farnborough International Air Show and arranged senior-level meetings for the Assistant Secretary for Industry and Analysis and the Acting Assistant Secretary for Global Markets with foreign government and industry officials as well as U.S. industry executives. 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 216 Written Impact Narratives (WIN) in FY 2018, slightly exceeding the number in FY 2017. 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 3,944 counseling sessions with approximately 1,877 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 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 Farnborough Air Show, the Singapore Air Show, Eurosatory, the Dubai Air Show, HeliExpo, and the Seoul International Aerospace and Defense Exhibition, among others.

Bureau of Industry and Security

During this fiscal year, the Bureau of Industry and Security (BIS) worked with industry and the interagency Space Working Group on identifying needed changes to the current regulations on spacecraft and related items. Updates to the Commerce regulations covering controls on satellite thrusters became final in August 2018. These updates were in response to industry requests. BIS also provided input to the Department in support of the National Space Council–directed activities. This information included inputs into the Department's Plan for Maintaining U.S. Leadership in Space Commerce as well as participating more formally with the Office of Space Commerce. BIS also participated in the Transportation Technical Advisory Committee discussions, which include aerospace-related topics.

Department of the Interior

DOI

Remotely sensed data and derived information contribute significantly 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) is both a user and a provider of remotely sensed data. The USGS manages the Landsat satellite series and a Web-enabled archive of global Landsat imagery dating back to 1972. Landsat represents the world's longest continuously acquired collection of space-based moderate-resolution land remote sensing data, and the entire archive became available for download at no charge in December 2008. The USGS also distributes aerial photography through The National Map, and it archives and distributes historical aerial photography; light detection and ranging (lidar) data; declassified imagery; hyperspectral imagery; data collected by Unmanned Aircraft Systems; and imagery from a variety of Government, foreign, and commercial satellites. These data are 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.

DOI Unmanned Aircraft System Kīlauea Eruption Response

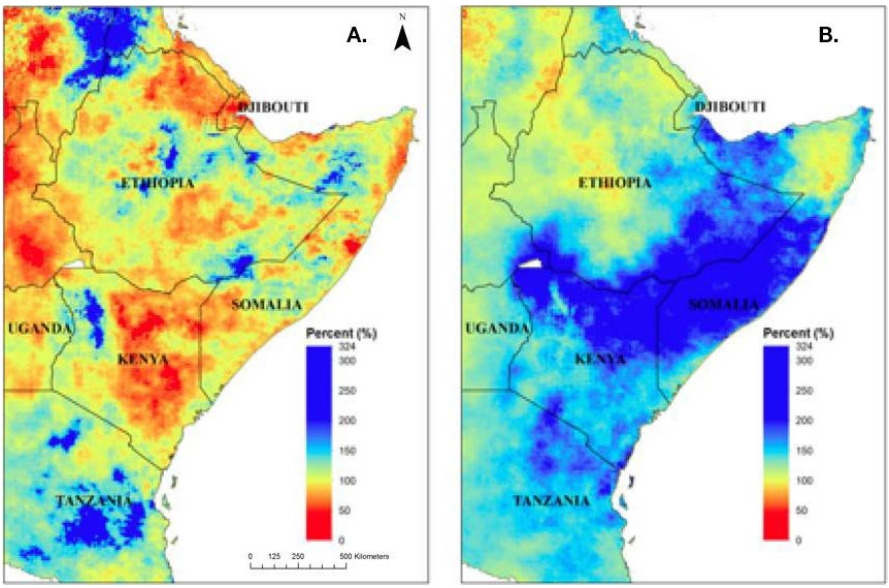
The 2018 eruption of the Kīlauea volcano in the Hawaiian islands is historically unprecedented in many ways, with explosions and repetitive large-scale collapse events at the volcano's summit and voluminous lava output in the Lower East Rift Zone (LERZ) that has strongly impacted communities in the lower district of Puna. Additionally, it marks the Federal Government's first UAS response to a volcanic eruption. The success of the UAS response relied on rapid and safe integration of UAS operations into temporary flight restriction areas, which required close operational coordination with the Federal Aviation Administration, emergency managers, land owners, and local operators. Once effective airspace coordination was achieved, researchers were able to provide a stream of quick-turnaround data products to scientists for quantitative use and to emergency managers for situational awareness. Integrating new gas sensors permitted volcanic gas emission measurements from inaccessible or hazardous areas, and live video streaming to emergency operations centers in Hilo and Honolulu supported the management of emergent public safety situations.

An assortment of rotor and fixed-wing UASes and sensors were used to monitor the eruption at both the summit and LERZ. UASes were equipped with gas sensors to monitor emission rates and concentrations, and visual and thermal cameras were used to provide videos for situational awareness. Repeat nadir videos were captured over sections of the lava channel to support eruption rate estimates, and photogrammetry surveys were conducted to create very-high-resolution digital elevation models (DEMs) and orthophotos. These data were used to monitor flow advance rates and erupted volume and provided updated topography for flow inundation modeling in the LERZ. A time series of DEMs of the summit captured caldera growth, including rate and volume of collapse, and orthophotos were used to map out fractures and ballistic fall fields. The remarkable datasets derived from these UAS surveys provided unprecedented monitoring data and truly show the utility of UASes for volcano monitoring.

Famine Early Warning Systems—Climate Outlook Analysis

The GeoCLIM climate analysis tool and the Climate Hazards Group Infrared Precipitation with Stations (CHIRPS) rainfall dataset were developed to support a request from the U.S. Agency for International Development Famine Early Warning Systems Network (FEWS NET). In May 2018, Kenya experienced extremely hazardous torrential rains. As climate models began to indicate that the development of an El Niño appeared likely, FEWS NET analysts became concerned about more flooding during the next rainy season (October–December). El Niño events are historically associated with above-normal rains in Kenya during this time period. A complicating factor, however, is that East African rains are also influenced by variations in the Indian Ocean Dipole (IOD), a measure of the east-to-west difference in Indian Ocean sea surface temperatures. Strong positive IOD events are associated with warm waters in the western Indian Ocean and above-normal rains in East Africa.

Would an El Niño alone be sufficient to produce extreme East African rains? Scientists at the USGS Earth Resources Observation and Science (EROS) Center and the University of California, Santa Barbara, developed the GeoCLIM tool so that scientists in developing countries can answer these types of questions. Using the GeoCLIM, two FEWS NET scientists (Gideon Galu and Laura Harrison) produced CHIRPS rainfall composites for previous El Niño October-to-December seasons that were not IOD events (1986, 1987, 2004, 2009, and 2014). Surprisingly, the rainfall outlook under these conditions tended toward slightly below normal. Galu also produced a composite for years that were both El Niño and positive IOD events (1982, 1991, 1994, 1997, 2002, 2006, and 2015). In this case, there is a strong propensity for above-normal rainfall. The results of this work indicate that El Niño alone is not typically sufficient to produce extreme rainfall during October–December. When El Niño and the IOD combine to produce large increases in onshore moisture transports and uplift, the risk of flooding is substantially increased. Because the state of the Indian Ocean evolves more rapidly than that of the equatorial Pacific, FEWS NET analysts may need to wait to see how it evolves.



October–December rainfall anomaly for El Niño years (A). October–December rainfall anomaly for years that were both El Niño and positive IOD events (B).

Integrated Remote Sensing and Modeling for Managing Wetland Wildlife Habitat

Approximately 90 percent of the naturally occurring wetlands in California's Central Valley (including the Sacramento–San Joaquin Delta) have been lost due to land-use change, yet the area remains a critical landscape for migratory waterbirds through a complex system of managed wetlands and post-harvest flooded agriculture. USGS researchers are working with the Nature Conservancy, the California Landscape Conservation Cooperative, and the U.S. Fish and Wildlife Service to prioritize the timing and location of water allocation to Central Valley croplands and wetlands to optimize habitat for migratory birds and the giant garter snake. As part of this project, the team is generating Central Valley–wide Landsat-based time-series maps (2007–17) of waterfowl food resource (moist soil seed) extents and relative productivity derived from Normalized Difference Vegetation Index (NDVI) greenness metrics. Valley-wide estimates of waterfowl food resources are needed to run bioenergetics models that support conservation planning. Given the extreme fluctuations in water availability, maps will also provide an annual record of how wetlands were managed.

Landsat Burned Area Products

Scientists at the USGS Geosciences and Environmental Change Science Center in Denver, Colorado, have led the development and validation of the Landsat Burned Area products. The algorithm producing the products identifies burned areas in Landsat images that have a spatial resolution of 30 meters and a temporal resolution of 16 days or more, depending on cloud cover. Fires are frequently unreported; consequently, existing fire databases are often incomplete. Furthermore, these databases often have location errors and records may be duplicated.

The Landsat Burned Area products (*https://www.usgs.gov/land-resources/nli/landsat/landsat-burned-area*) provide new and unique information about spatial and temporal patterns of fire occurrence that existing fire databases may lack, especially in areas such as the shrub and grassland ecosystems in the Great Plains and in the western and southeastern United States. In 2017, version 1 of the Landsat Burned Area path/row products was produced for 1984–2015 for the conterminous United States (CONUS) and released online (*https://doi.org/10.5066/F73B5X76*). In 2018, the USGS research team developed version 2 based on the Landsat Analysis Ready Data (ARD) for 1984–2017, and the version 2 products will be delivered through EarthExplorer (*https://earthexplorer.usgs.gov/*). Routine processing and delivery of 2018+ Landsat Burned Area products are expected to begin in the fall of 2018.

Landsat-Based Water-Use Mapping on a Cloud Computing Platform

Innovative cloud computing resources for remote sensing science have enabled advanced capabilities and analysis for solving complex large-scale data gap challenges within the USGS Water Availability and Use Science Program. With a vision for water budget estimation for the entire Nation, this research program integrates big data research and development into model applications, evaluation, and results.

Scientists at the USGS EROS Center collaborate with members from the Desert Research Institute using the Google Earth Engine (GEE) cloud platform to create nationwide quantitative evapotranspiration (ET) estimates with freely available Landsat thermal (infrared) imagery and weather data using the Operational

Simplified Surface Energy Balance (SSEBop) model. Multi-year nationwide results are supporting the National Water Census through field-level ET information across broad scales and timeframes.

Leveraging the power of GEE for model implementation, the team combined 30-meter Landsat data with state-of-the-art science and technology to quickly and efficiently map ET for water resource assessment, development, and management at the field and basin level. These developments demonstrate collaborative efforts to apply cloud computing for ET mapping at unprecedented scales so that results can be used to more accurately and efficiently inform water-use and water census programs.

The EROS Center develops and shares these ET products with USGS Water Science Centers, which are responsible for compiling water-use information every five years. This research and data integration also supports invested efforts of the Bureau of Reclamation to address water resource challenges facing the Nation.

Louisiana Barrier Island Habitat Mapping and Change Assessment

Barrier islands provide numerous invaluable ecosystem services, including storm protection and erosion control for the mainland, habitat for fish and wildlife, salinity regulation in estuaries, carbon sequestration in marsh, recreation, and tourism. These islands are dynamic environments due to their position at the land-sea interface. Storms, wave energy, tides, currents, and relative sea-level rise are powerful forces that shape barrier island geomorphology and habitats. To better inform both present and future management decisions, coastal resource managers require products developed from remote sensing, such as habitat maps, for insights into how these dynamic islands are changing over time. The Barrier Island Comprehensive Monitoring (BICM) program was developed by Louisiana's Coastal Protection and Restoration Authority (CPRA) and is implemented as a component of the System-Wide Assessment and Monitoring Program (SWAMP). The BICM program uses both historical and contemporary data collections to assess and monitor changes in the aerial and subaqueous extent of islands, habitat types, sediment texture and geotechnical properties, environmental processes, and vegetation composition.

The USGS Wetland and Aquatic Research Center provides geospatial support to the BICM program for mapping barrier island habitats and assessing habitat change over time. For this effort, habitat maps are being generated from high-resolution orthophotography and lidar data using object-based analyses in Trimble eCognition 9.3 for 2008 and 2015–16 for numerous coastal reaches in Louisiana. This software allows for a variety of data, such as aerial imagery and elevation data, to be integrated into a habitat-mapping process. The BICM program has developed two habitat classification schemes, which include a detailed 15-class and a general eight-class habitat scheme. The detailed scheme was developed specifically for this habitat-mapping effort and builds off the general scheme used in previous BICM habitat-mapping efforts. The additional classes developed in the detailed scheme are primarily used to further delineate various dune habitats, separate marsh and mangrove, and distinguish between beach and unvegetated barrier flat habitats. Spatial change analyses will be conducted between previously developed BICM habitat maps from 2005 and the 2015–16 habitat maps produced through this effort. The habitat maps and change assessment products developed through this project are being published as regional products and USGS data releases.

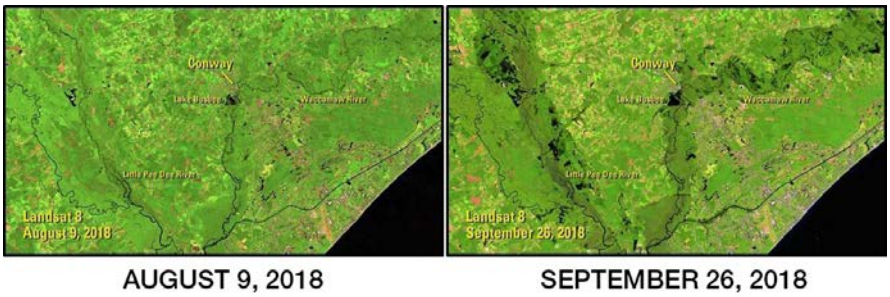
Mars Water Ice Resource Mapping

The USGS has been working with the High Resolution Imaging Science Experiment (HiRISE) team to locate the most promising deposits of water ice for future human colonies on Mars. By carefully targeting and analyzing the 25-centimeter/pixel images, the team discovered 100-meter-tall cliffs of almost pure water ice in locations that should be accessible to Mars landers (not too far from the equator and not too high in elevation). Both NASA and SpaceX have expressed interest in this information.

National Land Imaging Program Requirements, Capabilities and Analysis Activities

The USGS National Land Imaging Program (NLIP) has built a long-term capacity to collect and analyze land-imaging user requirements to advance the Nation's

operational and science objectives and better serve the land-imaging community. The USGS documents the land-imaging requirements of U.S. Federal, state/local, academic, industry, and international users to promote needs-driven, prioritized investment decisions for land-imaging systems, products, and services. Requirements are collected in a technology-agnostic format focused on spatial, spectral, and temporal needs, and they can be readily compared to U.S. Government, commercial, and international capabilities to identify technology solutions, data gaps, or collaborative opportunities. The USGS has also collected information from Earth science subject matter experts about their current use of Earth observation (EO) technologies, which is useful for understanding the utility of specific EO systems across and within communities of use. These data have been used to evaluate the relative impact of USGS ground-based, aerial, and satellite data within the USGS Mission Areas and across the Federal and non-Federal user communities, and to promote USGS and Department of the Interior participation and inclusion in a wide range of activities. Some examples are the broad representation of the USGS in the National Earth Observation Assessments, greater USGS participation in and user needs identification for the planned joint NASA–Indian Space Research Organization (NASA-ISRO) Synthetic Aperture Radar (SAR) Mission (NISAR), and greater participation in other Federal imagery program development. NLIP has also provided the primary set of user needs and analysis tools for early formulation of the Landsat 10 mission. The importance of USGS user requirements activities



Example image from NLIP gallery showing flooding from Hurricane Florence. These images are centered near Conway, South Carolina, and are 35 miles wide with north oriented to the top. Hurricane Florence hit the Carolina coast on September 14, 2018, but it took much longer for the full impact to emerge. Remotely sensed images show the slow devastation that 13 trillion gallons of rain can bring as it moves back toward the sea, with before (left) and after (right) images depicting water as black. Conway saw some of its most severe flooding nearly two weeks after the storm made landfall. The Landsat 8 image from September 26 (right) shows the Waccamaw and Little Pee Dee Rivers swollen on either side of the city.

continues to increase with the demand for smarter investments in land-imaging technology to support vital societal needs in agriculture, water quality and availability, disaster mitigation, land resource management, and economic development.

Patterns in the Landscape–Analyses of Cause and Effect

The USGS project Patterns in the Landscape–Analyses of Cause and Effect (PLACE) is leveraging improvements in image-processing capabilities to advance understanding of the driving forces and impacts of landscape change over time. PLACE researchers are synthesizing Landsat 30-meter imagery and ancillary products within a high-performance cloud-computing environment (Google Earth Engine) to monitor and assess flood hazards in the western United States from 1985 to 2015. The primary objective of the project is to investigate how climate processes influence the timing, location, and scale of flooding events in areas that are vulnerable to costly and dangerous repeat inundations. The project combines USGS streamgage station records with 30-meter-resolution maps of surface-water coverage produced by the European Commission's Joint Research Centre (JRC) and the USGS Dynamic Surface Water Extent (DSWE) project. Maps will be coupled with historical climate records, chronologies of extreme weather, and hydrogeomorphic information to help quantify the causes of inland flooding.

Resulting flood maps will also be intersected with annual maps of human land use (rural, urban, agricultural, etc.) to investigate how humans might either affect or be affected by floods. By understanding the causes and patterns of floods, USGS researchers can improve flood predictions and assist planners and first responders in anticipating future flood risks to human populations. PLACE will help fulfill goals set forth in the DOI Strategic Plan 2018–22 by better informing land-use planning with mapping and by monitoring and assessing natural-hazard risks for improved response planning.

Satellite-Based Tools for Invasive Buffelgrass Management

Invasive buffelgrass (*Pennisetum ciliare*) spreads easily in the Sonoran Desert ecosystem, where it forms a continuous fuel layer that carries fire across the

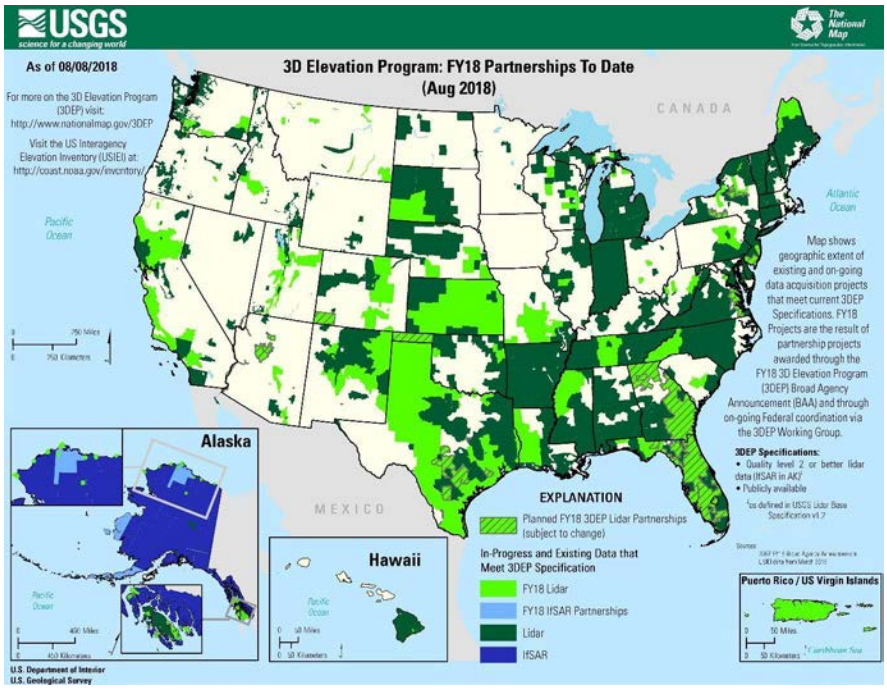
landscape, threatening native flora and fauna species. Current management of buffelgrass in Saguaro National Park (SNP) includes the targeted application of herbicide, which is most effective when the grass is photosynthetically active. The erratic, localized rain events characteristic of the Sonoran Desert complicate treatment by making it difficult to predict when buffelgrass will be green and therefore suited to treatment.

In collaboration with National Park Service (NPS) ecologists, USGS scientists are assisting buffelgrass eradication efforts by developing remote sensing–based strategies to identify infestation locations and optimal timing of herbicide treatment. A prototype Web-based application analyzes recent precipitation data to highlight when and where buffelgrass green-up thresholds have been reached. It also displays satellite-detected changes in greenness via Normalized Difference Vegetation Index values to show where vegetation green-up has occurred. To map where invasive buffelgrass is present, Climate Landscape Response (CLaRe) metrics, which leverage the correlation between precipitation amounts and NDVI, are used in classification algorithms. Nascent buffelgrass populations are detected by analyzing temporal patterns of climate-normalized CLaRe metrics across years.

Local partners and land managers involved in buffelgrass control efforts are providing feedback to guide the development of the application's design and content. The most useful features will be assimilated into the USA-NPN (National Phenology Network) suite of online phenological tools, which provide regional- to national-scale information to help guide science-based resource management actions.

The USGS 3D Elevation Program

The goal of the USGS 3D Elevation Program (3DEP) is to complete nationwide coverage of lidar data for the conterminous United States, Hawaii, and the U.S. territories and interferometric synthetic aperture radar (IfSAR) for Alaska by 2023, contingent upon sufficient funding. 3DEP is a cooperative program designed to meet the needs of a broad range of stakeholders and leverage substantial data



Status of 3DEP quality data as of July 2018.

investments and contributions through Federal, state, tribal, and private-sector partnerships. 3DEP relies on the expertise and capacity of private-sector mapping firms to acquire the data. High-resolution elevation data are essential to a broad range of applications, including infrastructure development, flood risk management, critical minerals assessment, emergency planning, energy development, precision agriculture, natural resources management, and more.

The USGS is responsible for the quality control, management, and delivery of 3DEP data, including lidar point clouds, digital elevation models (DEMs) at multiple resolutions (including one meter), and IfSAR orthorectified intensity images. As of May 2018, 3DEP-quality elevation data are available or in production for 48 percent of the Nation, including 96 percent of IfSAR data in progress or available for Alaska. 3DEP data are collected, quality-controlled, and delivered to meet community-accepted USGS specifications, enabling a broad range of applications that rely on consistent foundational data. 3DEP lidar and IfSAR data are publicly available free of charge at *http://viewer.nationalmap.gov/basic/*.

United States, Canada, and Mexico Publish First-Ever 30-Meter Land Cover for North America

The USGS Earth Resources Observation and Science (EROS) Center and collaborative agencies in Canada and Mexico have published the first-ever 30-meter-resolution consistent land-cover product for all of North America. This tri-national effort was completed under the umbrella of the North American Land Change Monitoring System (NALCMS), a collaboration between the governments of the United States, Canada, and Mexico coordinated by the Commission for Environmental Cooperation (CEC). NALCMS has previously delivered 250-meter-resolution land-cover and land-cover-change products for North America. The new 30-meter product was generated using Landsat imagery divided into 19 land-cover classes and will provide users with a better understanding of the dynamics and continental-scale patterns of North America's land cover at a scale that will facilitate regional and local analysis. NALCMS intends to produce this 30-meter product every five years to update the changing land cover of North America and to quantify change. This product is available for download from the CEC Web site at *http://www.cec.org/tools-and-resources/map-files/land-cover-2010-landsat-30m*.

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 partners, uses 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 utilizes acoustic geographic positioning systems, as well as 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, thermal imagery, radar imagery, sonar imagery, 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.

Comprehensive Invasive Phragmites Management Planning

The Comprehensive Invasive Phragmites Management Planning project was completed to create an adaptive management plan for invasive phragmites control in the Saginaw Bay of Lake Huron, Michigan. Phragmites is a tall grass that chokes shorelines, limiting access for recreation activities, displacing fish and native vegetation, and creating a fire hazard. The FWS research team integrated local and regional knowledge, high-resolution maps from remote sensing data, and modeling of nitrogen (N) loading and hydrological connectivity to identify the best phragmites treatment and monitoring strategies. The outputs of this grant are products of multi-disciplinary integrative efforts between Michigan Technological University, the University of Michigan, Michigan State University, Texas A&M, the University of Northern Iowa, the U.S. FWS, the Michigan Department of Natural Resources, and the Saginaw Bay Cooperative Invasive Species Management Area.

Remotely sensed data informed this project, including a review of historical (1938 to present) aerial imagery of four sites to determine pre-invasion ecosystem type (wetland, beach, open water, etc.). WorldView-2 (WV2) submeter satellite imagery is being used to map pre- and post-treatment conditions, allowing managers to quantify the effectiveness of various treatments, including herbicide and cutting/burning. For pre-treatment, in August 2016, the entire coastal area of Saginaw Bay and the Saginaw River (including all treatment areas) were mapped at a minimum mapping unit of 0.5 acre using interpreted WV2 data (*http://geodjango.mtri.org/coastal-wetlands/*). Post-treatment maps for summer 2017 were incomplete due to cloudy conditions, and 2017 imagery was available for only one of the four treatment areas (see figure). Imagery from the summer of 2018 will be downloaded for the four sites. Peak growing season post-treatment imagery provides needed information on the distribution of phragmites killed, standing dead, and mowed vegetation, as well as missed phragmites and regrowing vegetation. This detailed site-level information is important for adaptive management; such a bird's-eye view is particularly valuable for large areas that are impassable by foot and those requiring large amounts of staff time to complete.

Radar View of Fall Avian Migration in Cleveland, Ohio

Documenting bird and bat migration is challenging because migration activity is sporadic, and nocturnal migrants (most aerial vertebrate migrants) are difficult to observe. FWS uses mobile avian radars to study the timing, duration, and activity patterns of birds and bats as they move through the Great Lakes (*https://www.fws.gov/radar*). Each radar unit has a horizontal antenna that scans 360 degrees just above the horizon to monitor flight directions, as well as a vertical antenna that scans a vertical slice of the sky to measure passage rates and altitudes. In the fall of 2017, the FWS team deployed a radar unit along Lake Erie in Cleveland, Ohio, to study how migrants move through an urban setting, use the lake shoreline, and traverse (or avoid) Lake Erie. Understanding the paths and timing of migration and how birds and bats use airspace along Great Lakes coastlines informs risk assessment for coastal development and allows managers to prioritize conservation efforts.

Seasonal Drought in Sage-Grouse Habitat Influences Resource Availability and Population Dynamics

The North American semiarid sagebrush biome exhibits considerable climatic complexity driving dynamic spatiotemporal shifts in primary productivity. Greater and Gunnison sage-grouse are adapted to patterns of resource intermittence and rely on stable adult survival supplemented by occasional recruitment pulses when climatic conditions are favorable.

Predictions of intensifying water scarcity raise concerns over new demographic bottlenecks impacting sage-grouse populations in drought-sensitive landscapes.

FWS researchers estimated biome-wide mesic resource productivity from 1984 to 2016 using remote sensing to identify patterns of food availability influencing selective pressures on sage-grouse. Productivity was linked to abiotic factors to examine effects of seasonal drought across time, space, and land tenure, with findings partitioned along gradients of ecosystem water balance within the Great Basin, Rocky Mountains, and Great Plains regions. Precipitation was the driver of mesic resource abundance, explaining ≥70 percent of variance in drought-limited

vegetative productivity. Spatiotemporal shifts in vegetation abundance were apparent given biome-wide climatic trends that reduced precipitation below three-quarters of normal in 20 percent of the years. Drought sensitivity structured grouse populations wherein landscapes with the greatest uncertainty in mesic abundance and distribution supported the fewest grouse. Privately owned lands encompassed 40 percent of sage-grouse range but contained a disproportional 68 percent of mesic resources, shifting in part the perception of the species' reliance on public lands.

Regional drought sensitivity acted as ecological minimums to influence differences in landscape carrying capacity across sage-grouse range. The model depictions likely reflect a new normal in water scarcity that could compound impacts of demographic bottlenecks in the Great Basin and Great Plains. Long-term population maintenance depends on a diversity of drought-resistant mesic resources that offset climate-driven variability in vegetative productivity. A holistic public-private lands approach to mesic restoration is needed to offset a deepening risk of water scarcity.

Tree Canopy Mapping Across the Golden-Cheeked Warbler Breeding Range

A key vegetation parameter important to maintaining golden-cheeked warbler (hereafter warbler) breeding habitat is the amount of broadleaf versus Ashe juniper tree cover on a site. Mixed composition woodlands with mature Ashe juniper trees provide enhanced foraging opportunities through high arthropod diversity and supply juniper bark used for nesting. FWS scientists sought to map broadleaf and juniper tree canopy at 1-meter scale across the entire 85,500-square-kilometer breeding area in central Texas to model warbler density from point count data. High spatial resolution (0.5-meter to 1.0-meter pixels) leaf-on (2016) and leaf-off (2014 to 2015) digital color infrared aerial photography is periodically collected for Texas through the National Agriculture Imagery Program (NAIP) and Texas Orthoimagery Program (TOP).

The FWS team used Random Forest (RF) classification tree models optimized with Recursive Feature Elimination (RFE) to select a subset of important predictor variables from seasonal images. Spectral features included blue, green, red, and near-infrared bands; the Normalized Difference Vegetation Index; and the

difference between leaf-on and leaf-off NDVI values (dNDVI). Total, Ashe juniper, and broadleaf percent tree cover estimated at 1-hectare spatial scale showed a strong positive relationship (r^2 = 0.93, r^2 = 0.83, r^2 = 0.73, respectively), with independent canopy intercept data collected within 100-meter by 100-meter field plots at a 10-meter spacing with a moosehorn densitometer. Field plots (n = 98) collected in 2012 were limited to Balcones Canyonlands National Wildlife Refuge, Texas. The FWS team is collecting additional data from across the warbler's breeding range to evaluate and refine digital tree canopy data that will be used to estimate warbler density.

Mapped tree cover and warbler density data will help prioritize critical habitat areas for conservation and habitat improvement efforts in central Texas.

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 covering 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.

Satellite Data for Offshore Air Quality Applications

BOEM is working with the NASA Atmospheric Chemistry and Dynamics Laboratory at Goddard Space Flight Center to assess the probability of using satellite data for air-quality applications, specifically through the estimation and monitoring of offshore ground-level concentrations of pollutants and through

improvements and validations of BOEM's existing emissions inventories and photochemical modeling. BOEM is required to analyze OCS oil and gas activities' air quality impacts to the states as mandated by the Outer Continental Shelf Lands Act (OCSLA). These assessments are used by BOEM in National Environmental Policy Act (NEPA) Environmental Assessments (EAs) and Environmental Impact Statements (EISes). This study seeks to improve and add to the data for these assessments in support of BOEM's air quality regulations and NEPA analyses.

The Clean Air Act (CAA) requires the U.S. Environmental Protection Agency (USEPA) to set the National Ambient Air Quality Standards (NAAQS) for atmospheric pollutants; USEPA has set standards for six criteria pollutants: carbon monoxide (CO), lead (Pb), nitrogen dioxide (NO_2), ozone (O_3), particulate matter ($PM_{2.5}$ and PM_{10}), and sulfur dioxide (SO_2).

The OCSLA requires BOEM to ensure compliance with the NAAQS to the extent that OCS oil and gas exploration, development, and production activities can greatly impact the air quality of any state. Satellites have become increasingly capable of identifying and measuring the quantity of certain criteria NAAQS and their precursors, as well as assessing the impact of pollution on visibility. Although this capability has been identified, it has not previously been employed in the offshore environment.

In this study, NASA is improving the operational satellite NO_2 data product, addressing several issues that will likely improve the use of the data over open water. With an improved NO_2 product, the study will 1) estimate NO_2 concentrations around offshore facilities, 2) determine the contribution of onshore emissions (such as specific refineries, power plants, and cities) to offshore air quality and vice versa by analyzing wind flow patterns and daily NO_2 data, and 3) derive long-term trends over the last decade.

Additionally, a research cruise in the Gulf of Mexico is planned as part of this study to validate the remotely sensed data using NASA equipment to measure near sea level the same constituents observed by satellite. A Web site—Satellite Continental and Oceanic Atmospheric Pollution Experiment (SCOAPE)—is under development to share this project's goals and progress.

Bureau of Land Management

The Bureau of Land Management (BLM) leverages ground, airborne, 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; 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, field-based data are used 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.

Post-Fire Emergency Stabilization and Rehabilitation Imagery Support

The BLM National Operations Center (NOC) provides remotely sensed geospatial data products to support fire 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 completing key objectives, including monitoring vegetation treatments and reforestation and rehabilitating land cover. To support 2018 ESR efforts, the NOC is providing products derived from the European Space Agency's Sentinel-2 system to requesting officials. The products include 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), and Delta NBR (dNBR) products are also derived and disseminated. Finally, the NOC provides a classification product identifying burned and unburned cover. These data and maps provide managers with timely information on the impact of fire in their landscapes and are accessible via download and as Web-based image and map services.

Tracking BLM Energy Development in the Permian Basin

The Permian Basin in New Mexico and Texas is a leading source of oil production for the United States and is experiencing rapid energy development. The BLM holds millions of acres of mineral estate—including within the Permian Basin—which must be administered. Upon request from the Carlsbad Field Office (CFO), the National Operations Center (NOC) and the New Mexico State Office (NMSO) have partnered in a pilot project to use remote sensing products to easily and efficiently identify energy development within their region. To support this effort, the NOC is providing multi-date Sentinel-2 imagery to the CFO. The data have been spectrally subset from 13 to 10 bands (visible to shortwave-infrared) and have been spatially subset to the Permian region to reduce file storage space. With a revisit period of five days or less, Sentinel-2's temporal resolution dramatically increases the ability of land-management officials to delineate rapid land-cover changes. These data will be made available to BLM officials as Web-based image services for ease of access and use. Other custom products that can assist the analyst in identifying cover trends between dates—such as NDVI, (NBR), dNDVI, and dNBR—can also be derived. Finally, the NOC is investigating techniques to efficiently map wellpad development, and associated transportation infrastructure, using multi-temporal imagery and object-oriented classification software.

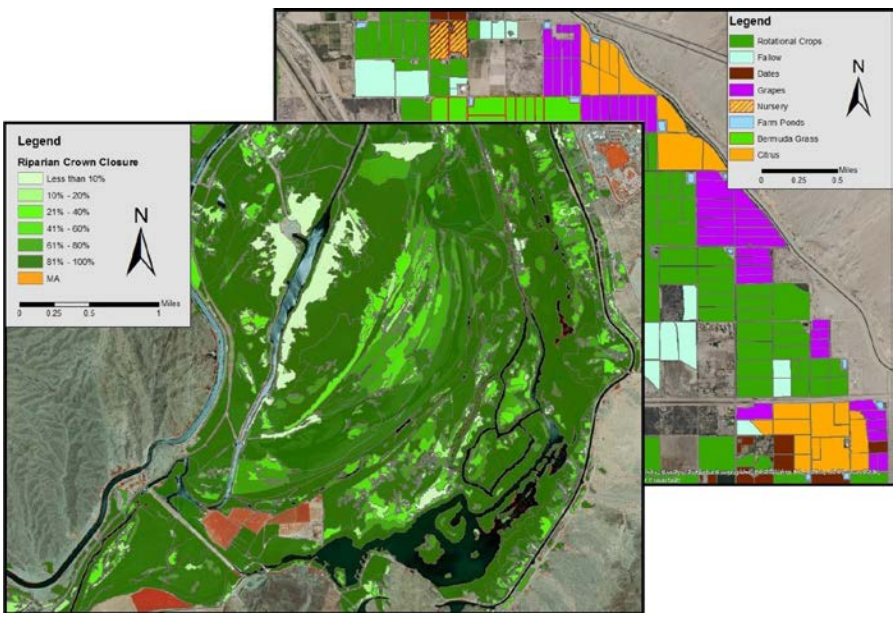
U.S. Bureau of Reclamation

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. 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

The Colorado River is the principal source of water for agriculture and riparian vegetation in Arizona, southern California, and southern Nevada. To account for water use by each state or individual and to verify lands fallowed for conservation programs and other water management needs, BOR routinely 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. Multispectral satellite and aerial images are analyzed in combination with other spatial data in a Geographic Information Systems (GIS) environment to generate information regarding crop and riparian types, acreages, and water-use estimates.



The BOR uses remote sensing and GIS processes to map crop and riparian vegetation groups and to estimate the evapotranspiration associated with these groups. Above are examples of the Riparian database at Laguna Dam in Arizona (left) and agricultural database near Coachella, California (right).

These data and information assist 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 mainstream of the Lower Colorado River. This program is an example of implementing remote-sensing-based methodologies to routinely meet BOR's water management needs.

Rapid Canal and Levee Seepage Detection

In the United States alone, there are currently over 100,000 miles of canal and levee embankments and approximately 79,000 earthen dams on the national inventory list. Many of these structures are reaching or have surpassed their initial design life. Most earthen embankment structures are over 50 years old, and many are greater than 80 years old. Development and urban encroachment along this aging infrastructure increase risk associated with seepage and internal erosion-caused failures. Additionally, water conveyance systems are known to lose large quantities of water due to distributed seepage along embankments. As a result, there is a need for proactive yet efficient characterization of these vast infrastructural systems by means of rapid reconnaissance surveying technologies.

To address these issues, researchers at the BOR are working with three area offices (Provo Area Office, Lahontan Basin Area Office, and Western Colorado Area Office) to develop new approaches for rapid earthen canal and levee seepage detection and characterization. One new approach uses remote sensing data, including NDVI images, combined with frequency-domain electromagnetic (FDEM) and magnetic gradiometry profiling surveys conducted along canal embankments using a vehicle-towed non-magnetic/non-metallic cart platform. This approach to field data collection allows for tens of miles of detailed geophysical profiling data to be collected per day.

The research team has been funded through the BOR's Science and Technology Program and is working toward developing semiautomated and robust workflows for combining and interpreting these various data types, including data fusion, attributes analysis, and machine learning, to better identify and differentiate between anomalies related to seepage, unauthorized penetrations, or other unhealthy conditions. Implementation of rapid reconnaissance tools of this sort could provide a

list of "hot spots" that could be prioritized in terms of more-focused investigation efforts (e.g., using higher-resolution geophysical methods or geotechnical investigation techniques at locations of elevated concern). This approach to identifying abnormal seepage or saturation levels within canal levees (based on electrical conductivity signatures/anomalies/trends) will help save a considerable amount of resources being spent on embankment assessment, will help reduce risk associated with embankment failures, and can help to identify and address unwanted water conveyance seepage losses.

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 Global Positioning System (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. Aerial photography and satellite imagery have been utilized to compile vegetation maps—a monumental task, given that the agency has responsibility for over 80 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 takes advantage of the free Landsat archive to quantify decadal changes in glacier ice cover and document land-cover change in national park units. Using the Landsat archive, the NPS has been a beneficiary of and a partner in interagency efforts to map all large wildland and prescribed fires as part of the DOI Monitoring Trends in Burn Severity project. GPS supports field data collection, navigation, and search-and-rescue operations conducted by the agency.

Detection of Rain-on-Snow Events Across Alaska

Snowmelt and rain-on-snow (ROS) events enhance the liquid water content of a snowpack, which affects snow properties such as depth, density, grain size, and extent. These changes are associated with transfers of latent and sensible heat

and create a positive feedback that accelerates snowmelt processes. Wet snow can affect high-latitude ecosystems at multiple spatial and temporal scales, impacting the hydrology, carbon cycle, wildlife, and human interactions.

Our knowledge of the spatiotemporal patterns in ROS events and their response to climatic variability is limited by the sparse network of in situ climate observations and landscape heterogeneity in Alaska.

With this analysis, NPS researchers inform this knowledge gap by combining observations from overlapping satellite optical-infrared and microwave sensors to improve understanding of the timing and distribution of ROS events across Alaska. The NPS team utilized vertically and horizontally polarized daily brightness temperature images at six kilometers from the 19- and 37-gigahertz bands of the Advanced Microwave Scanning Radiometers and integrated them with the 500-meter snow-cover extent product derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) to determine the timing and distribution of wintertime (November–March) ROS events during water years 2003–16.

Results revealed markedly higher ROS frequency in the southwest and central portions of Alaska relative to other regions. Timing of the events was most prominent in November and December, coinciding with warm temperature anomalies. ROS events in Alaska's North Slope were rare during the winter months and typically occurred during periods of above-normal temperatures.

Furthermore, findings determined that as the Arctic amplification of global temperatures continues, wintertime ROS events will likely become more prominent in Alaska's southwest and interior regions. The ROS record created from this work is publicly available to contribute to Alaska's monitoring of snow-cover properties, as it will influence regional transportation, infrastructure, and wildlife populations moving into the future.

Vegetation Mapping of Everglades National Park and Big Cypress National Preserve

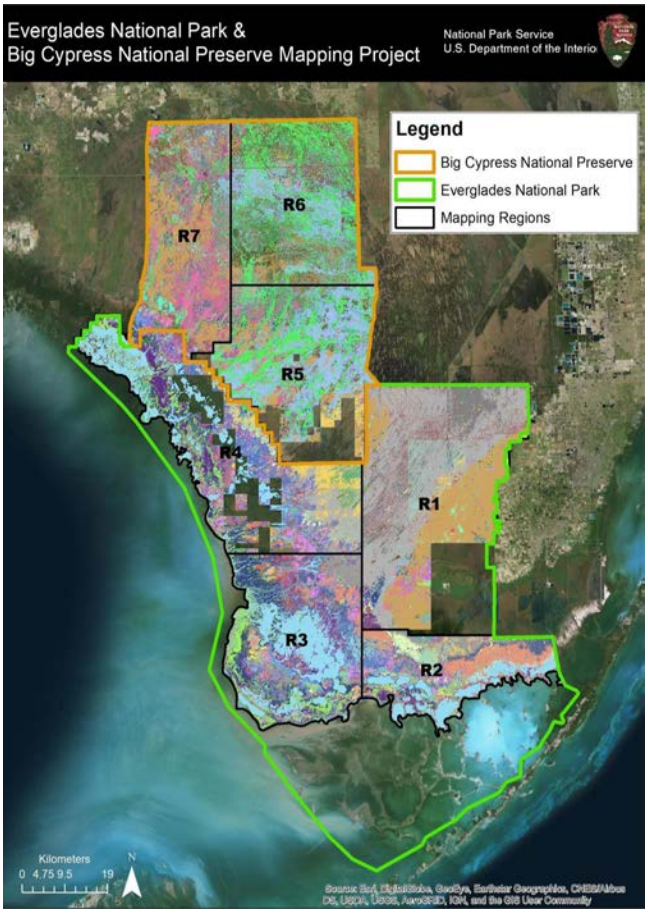
The Everglades National Park (EVER) and Big Cypress National Preserve (BICY) vegetation-mapping project is a component of the Comprehensive Everglades Restoration Plan (CERP). The CERP is a cooperative effort between the South

Florida Water Management District, the U.S. Army Corps of Engineers (USACE), and the NPS Vegetation Inventory Program (VIP), with funding provided by the NPS VIP and the USACE. The goal of the project is to produce a spatially and thematically accurate vegetation map of EVER and BICY that will serve as baseline conditions to 1) document changes to the spatial extent, pattern, and proportion of plant communities as they respond to management-driven hydrologic modifications resulting from the implementation of the CERP and the Western Everglades Restoration Project and 2) provide vegetation and land-cover information to NPS park managers and scientists for use in park management, resource management, research, and monitoring.

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, 1 through 4; and three regions in BICY, 5 through 7. Photo-interpretation is performed by superimposing a 50- by 50-meter (¼-hectare) grid cell vector matrix over stereoscopic, 0.30-centimeter spatial resolution, color infrared aerial imagery on a digital photogrammetric workstation. Photo-interpreters identify the dominant community in each cell by applying majority-rule algorithms, recognizing community-specific spectral signatures, and referencing an extensive ground-truth database.

Approximately 78 percent of the entire project area is mapped. EVER is 73 percent complete, while BICY is 92 percent complete. Regions 2, 3, and 7 are mapped. The Region 2 vegetation map has a thematic accuracy of 88.6 percent with a lower 90th percentile confidence level of 84.6 percent and is available for download (*https://irma.nps.gov/DataStore/Reference/Profile/2243281*). The thematic accuracy of the Region 3 vegetation map is 89.4 percent with a lower 90th percentile confidence level of 85.6 percent.

This map will be available for download in fall 2018 (*https://irma.nps.gov*). The thematic accuracy of the Region 7 vegetation map is 85 percent with a lower 90th percentile confidence level of 82 percent. The final report for Region 7 is pending peer review.



Footprint of the Everglades National Park and Big Cypress National Preserve vegetation-mapping project showing mapping regions and progress to date.

Office of Surface Mining Reclamation and Enforcement

The Office of Surface Mining Reclamation and Enforcement (OSMRE) remote sensing program provides OSMRE offices, states, and tribes with the necessary tools to use remote sensing technologies to support Titles IV (Abandoned Mine Lands) and V (Regulation of Current Mining) of the Surface Mining Control and Reclamation Act of 1977 (SMCRA). As part of this support, the OSMRE remote sensing program provides high-resolution satellite imagery, aerial photography, and lidar data to conduct analyses of terrain, vegetation, and hydrologic function on active mine sites to ensure that reclamation is consistent with the approved mining permit. These data are also used to support inventory, monitoring, and assessment

of abandoned mine land features to ensure that there is no threat to the environment or to health and human safety.

Cottonwood-Wilberg Mine, Emery County, Utah, Reclamation

The OSMRE Western Region worked with the State of Utah Division of Oil, Gas, and Mining to monitor reclamation efforts at Cottonwood-Wilberg Mine in Emery County, Utah, using remote sensing change detection of historical photography and land-use records. OSMRE purchased high-resolution lidar and orthophotography from Juniper Unmanned of the site before major earthwork commenced in September 2017. OSMRE used Digital Globe, the European Space Agency Sentinels, and Planet Labs satellite imaging to monitor the in-progress reclamation work. The state inspectors shared monthly photographs of the site with OSMRE to verify observations made with remote sensing images. Upon completion of the reclamation work, OSMRE and Utah state personnel collected terrestrial lidar and photography in May 2018. In June 2018, the Trail Mountain Fire started and burned more than 17,000 acres north of the site. OSMRE is continuing to monitor the reclamation area for possible flooding impacts using synthetic aperture radar and high-temporal-resolution imaging. Having historical imagery from 1936 forward helped understand the dynamics of the natural landscape and provides context for ongoing monitoring.

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 2018 related primarily to commercial communications satellites and Earth observation satellites, as well as experimental satellites.

The FCC took several significant actions in administrative and rule-making proceedings in FY 2018, among them these:

- On April 17, 2018, the FCC proposed rules to create a streamlined application process for a category of satellites often referred to as "small satellites." Geared primarily toward commercial small satellites and small satellite systems, the FCC's proposals would create a path for streamlined processing 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. As proposed, applicants with systems meeting these characteristics would be able to take advantage of faster processing times and lower fees.
- On June 18, 2018, as part of its ongoing "Spectrum Frontiers" proceeding, the FCC proposed rules to permit the licensing of individual fixed-satellite service earth stations in the 50.4- to 51.4-gigahertz frequency band. The FCC proposed sharing criteria between earth stations and the Upper Microwave Flexible Use Service (UMFUS), as well as constraints on the

number of permitted earth stations on both a per-county and per–partial economic area (PEA) basis.

- On September 27, 2018, the FCC adopted new rules applicable to earth stations in motion (ESIMs), which are earth stations located aboard ships, aircraft, and vehicles. This action simplified the FCC's rules and made additional frequency bands available for use by these types of earth stations. In addition, the FCC proposed to make available even more frequencies for communications with ESIMs.

During FY 2018, 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 3, 2017, the FCC issued a ruling outlining the conditions under which Telesat Canada can obtain a license for earth stations in the United States for use with its system, which will operate under the authority of Canada. The system will consist of up to 117 satellites operating at approximate altitudes of 1,000 kilometers and 1,250 kilometers and utilizing frequencies in the Ka-band. The satellites are designed to provide broadband connectivity in the United States and throughout the world.
- On November 3, 2017, the FCC issued a ruling outlining the conditions under which Space Norway AS can obtain a license for earth stations in the United States for use with its satellite system, which will operate under the authority of Norway. The system will consist of up to two satellites, operating in an orbit with an apogee of approximately 43,500 kilometers and a perigee of approximately 8,000 kilometers and utilizing frequencies in the Ku- and Ka-bands. This satellite system is designed to provide broadband connectivity in high-latitude regions around the world, including Alaska.
- On March 6, 2018, the FCC issued a ruling modifying the existing earth station licenses of Iridium Carrier Services, LLC, and Iridium Satellite, LLC, to enable the operations of new user terminals that can take advantage of the capabilities of the second-generation satellites in the Iridium satellite system, operating in the mobile-satellite service.

- On March 29, 2018, the FCC authorized Space Exploration Holdings, LLC (SpaceX), to construct, deploy, and operate a satellite system consisting of 4,425 satellites operating at approximate altitudes of 1,100–1,300 kilometers and utilizing the Ku- and Ka-bands. This large, nongeostationary satellite constellation is designed to provide broadband connectivity in the United States and throughout the world.
- On June 6, 2018, the FCC granted a request from O3b Limited concerning proposed modifications to its satellite system, operating under the authority of the United Kingdom, with earth stations in the United States. As modified, the system would include up to 42 satellites, operating at an approximate altitude of 8,000 kilometers and utilizing frequencies in the Ka- and V-bands. This nongeostationary satellite constellation is designed to provide broadband connectivity in the United States and throughout the world.
- On June 6, 2018, the FCC authorized Audacy Corporation to construct, deploy, and operate a satellite system consisting of up to three satellites operating at an approximate altitude of 13,900 kilometers and utilizing the Ka- and V-bands. This satellite system is designed to provide commercial tracking and data relay services for other nongeostationary satellites.
- On August 16, 2018, the FCC authorized Karousel Satellite, LLC, to construct, deploy, and operate a satellite system consisting of up to 12 satellites operating in an orbit with an apogee of approximately 40,000 kilometers and a perigee of approximately 31,500 kilometers and utilizing the Ku- and Ka-bands. This nongeostationary satellite constellation is designed to distribute video and data to consumers in the United States and throughout the world.

The FCC also granted authority to Planet Labs, Inc., and Astro Digital US to deploy and operate nongeostationary small satellites in low-Earth orbit, primarily for remote sensing activities, specifically:

- December 8, 2017: To Planet Labs, Inc., to construct, deploy, and operate three satellites for the purpose of a propulsion system demonstration, to be deployed to orbital apogee altitudes of approximately 550 kilometers.

- December 14, 2017: To Astro Digital US, Inc., to construct, deploy, and operate one Landmapper-BC satellite at orbital altitudes between 475 and 625 kilometers.
- August 1, 2018: To Astro Digital US, Inc., to construct, deploy, and operate four additional Landmapper-BC satellites at orbital altitudes between 475 and 625 kilometers.

In addition, on December 5, 2017, the FCC granted authority to Space Logistics, LLC, to construct, deploy, and conduct telemetry, tracking, and command functions for a satellite servicing vehicle to be used to extend the mission lifetime of client geostationary satellites. The authorization includes operations following deployment from the launch vehicle, during orbit-raising maneuvers, and during rendezvous and docking with the Intelsat-901 satellite in an orbit several hundred kilometers above the geostationary arc. Additional operations are contemplated and will require authorization as plans are finalized.

In FY 2018, the FCC authorized a number of other commercial communication satellite deployments and operations. These authorizations included the following:

- March 8, 2018: To SES Americom, Inc., to operate a C-band satellite, to be located at the longitude 139.0° west orbit location.
- March 20, 2018: To Hughes Network Systems, LLC, to construct, deploy, and operate a Ka- and V-band satellite to be located at the longitude 95.2° west orbit location.
- April 25, 2018: To ES 172, LLC, to operate a C- and Ku-band replacement satellite located at the longitude 172° east orbit location.
- May 10, 2018: To Intelsat License, LLC, to construct, deploy, and operate a C-, Ku-, and Ka-band satellite to be located at the longitude 133.0° west orbit location.
- June 26, 2018: To Intelsat License, LLC, to construct, deploy, and operate a C- and Ku-band satellite to be located at the longitude 62.0° east orbit location.
- July 12, 2018: To Intelsat Licensee LLC, to construct, deploy, and operate a C- and Ku-band satellite to be located at the longitude 169.0° east orbit location.

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 activities ranging from remote sensing missions, such as collecting data on the atmosphere and oceans and measuring solar radiation, to missions testing the performance of certain technologies in space, such as radio equipment, satellite propulsion systems, and batteries, as well as the development of remote sensing platforms and testing of satellite relay communications for future commercial use. The FCC also granted experimental licenses in FY 2018 for inter-satellite communications between existing nongeostationary satellite constellations and experimental small satellites. Other experimental grants by the FCC included grants for communications associated with launch vehicles and for the testing of new telecommunications satellites.

On April 12, 2018, the FCC released an enforcement advisory regarding compliance with the requirement that satellite system operators obtain an FCC authorization for space station and earth station operations. The enforcement advisory reminded satellite system operators that the FCC had previously provided guidance concerning licensing of nongovernmental small satellites and that compliance with requirements for the licensing of satellite communications is not optional. Among other things, the advisory described why a license is needed, cautioned satellite operators not to provide a satellite that does not have an FCC license to a launch service provider for integration into a deployment device or launch vehicle, and detailed potential risks for launch service providers regarding the integration of satellites that do not have a current FCC authorization.

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 16, 2017: The FCC granted Intelsat License, LLC, special temporary authority to drift the Intelsat 16 satellite to the longitude 76.2° west orbit location and operate the satellite at that location in order to assist a customer in responding to the damage caused by Hurricane Maria to the

communications networks in Puerto Rico. The FCC granted extensions of this special temporary authority on November 17, 2017; November 30, 2017; and July 5, 2018. The FCC granted a license modification for these operations on July 26, 2018.

- November 2, 2017: The FCC granted SES Americom, Inc., special temporary authority to continue to conduct operations in connection with maneuvering the AMC-9 satellite to a disposal orbit. The satellite had previously suffered a significant anomaly. The FCC granted an extension of this special temporary authority on December 6, 2017. The satellite ultimately was disposed of at an altitude that meets international guidelines, with a perigee of 277 kilometers above the geostationary arc and an apogee of 430 kilometers above the geostationary arc.
- On November 9, 2017: The FCC granted Hughes Network Systems, LLC, special temporary authority to extend the service coverage area of the JUPITER 2 satellite at the longitude 97.1° west orbit location to the U.S. Virgin Islands to support recovery operations in the Caribbean following Hurricane Maria. The FCC subsequently granted a license modification for these operations on January 18, 2018.
- February 14, 2018: The FCC granted the request of ES 172, LLC, to relocate the EUTELSAT 172A satellite to the longitude 174.0° east orbit location, where it will operate in accordance with the International Telecommunications Union filings of Cyprus.
- May 24, 2018: The FCC granted the request of Planet Labs, Inc., to revise certain identified earth station locations and permit three of the satellites in its nongeostationary satellite orbit system to add an Automatic Identification System (AIS) receiver system for the purpose of demonstrating additional satellite capabilities.
- July 19, 2018: The FCC granted the request of Planet Labs, Inc., to permit up to 120 of the satellites in its nongeostationary satellite orbit system to operate at altitudes greater than 550 kilometers, rather than 500 kilometers.

The FCC also added a non-U.S.-licensed space station 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. In particular, on August 16, 2018, the FCC added Eutelsat S.A.'s EUTELSAT 133WA satellite to the permitted list, operating under the authority of France and using the Ku-band at the longitude 132.85° west orbit location.

During FY 2018, the operator of the FCC-licensed Iridium constellation continued the process of launching new satellites, begun in FY 2017, to replace the aging satellites in its 66-satellite constellation. As part of that process, in FY 2018 the operator removed 45 satellites from their operational orbits for purposes of disposal. At the end of the fiscal year, 33 of those satellites had reentered Earth's atmosphere. The remaining 12 of those satellites were in orbits from which they can be expected to reenter within 25 years, and most by 2020.

U.S. Department of Agriculture

USDA

Remotely sensed data and derived information support mission-critical work of the U.S. Department of Agriculture (USDA). A wide variety of data and technology, including aerial and satellite imagery and ground-based collections validated with GPS, are used in daily operations. Business requirements that inform specifications in USDA image acquisition contracts continue to result in heavy reliance on crewed aircraft–based imagery collection.

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. Just a few 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 were to support 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 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 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 2018 were Aberdeen Proving Grounds, Maryland; Edwards Air Force Base (AFB), California; Fort Bragg, North Carolina; and Vandenberg AFB, California.

FSA also uses remotely sensed data collected from space-based systems, such as the Moderate Resolution Imaging Spectroradiometer (MODIS), the Advanced Wide Field Sensor (AWiFS), 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 DigitalGlobe's Enhanced View Web Hosting Service (EVWHS) during 2018. 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) Office of Global Analysis (FAS/OGA) 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. 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 global monthly crop production, supply, and distribution (PSD) data from the USDA's

WASDE report on the FAS PSD Web site: *https://apps.fas.usda.gov/psdonline/app/index.html#/app/home*.

During 2018, the International Production Assessment Division (IPAD) operated the remote sensing program at FAS/OGA. 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 and Sentinel 2A and 2B served as the primary satellites used by FAS/OGA/IPAD for mapping crop area and crop type for numerous countries worldwide, whereas NASA's MODIS sensor, on board the Aqua and Terra satellites, is 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 easily allowed public users to analyze and compare current crop conditions with past years' crop conditions (*http://glam1.gsfc.nasa.gov/*). FAS/OGA 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/OGA also maintained several public global agricultural datasets by processing, archiving, and displaying a variety of satellite imagery products on the Web. The FAS/OGA Crop Explorer Web system allows the user 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) monitored and displayed 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. (See *http://www.pecad.fas.usda.gov/cropexplorer/*.)

FAS/OGA 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, and it is expected that the SMAP two-layer soil moisture product will operate at 10-kilometer resolution by 2020.

FAS/OGA 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 2018, the USDA/FAS purchased satellite imagery with 22-meter spatial resolution from the Deimos-1 and UK-DMC2 and archived at SIA's AE. FAS/OGA/SIA also provided funding to collect AWiFS (56-kilometer) and Linear Imaging Self Scanning (LISS)–III Sensor (24-kilometer) imagery from the Indian Resourcesat–2 (IRS-2) satellite, and the IRS-2 imagery is now available for download through the USGS Earth Explorer Web site 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 2018 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. This work encompasses partnerships with states, tribes, and other Federal agencies to address forestry and natural resource issues; the administration and management of 155 national forests and 20 national grasslands collectively known as the 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 2018, the USFS collaborated with NASA, NOAA, the USGS, and other agencies to apply operational satellite and airborne imagery and the most advanced remote sensing and geospatial technologies. Specific accomplishments included the following:

- USFS collected comprehensive Earth Observing System (EOS), MODIS, and Suomi National Polar-orbiting Partnership (Suomi NPP) Visible Infrared Imaging Radiometer Suite (VIIRS) direct-broadcast data and Landsat 8 Operational Land Imager (OLI) data via the USGS's Earth Resources Observation and Science (EROS) for the United States and Canada. Provided operational processing and disseminate 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/*.) More than 5.65 million users accessed the Active Fire Mapping Web site in FY 2018.
- USFS continued activities with NASA Goddard Space Flight Center's Direct Readout Laboratory under a USFS-NASA interagency agreement to test and operationally implement direct-readout 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/*.)
- USFS 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 provide early warning information to Forest Health Protection staff of forest areas potentially affected by pests/pathogens and support targeted monitoring and suppression activities. Also initiated efforts to leverage operational VIIRS imagery for comprehensive forest monitoring and ensure future continuity with current MODIS-based monitoring approaches. (See *http://foresthealth.fs.usda.gov/portal/Flex/FDM?dL=0*.)
- USFS utilized MODIS imagery to conduct coarse-level forest damage assessments for large geographic areas of the continental United States in the immediate aftermath of several 2018 hurricane events (Florence and Michael). This strategic information supports the agency in targeting areas for fuels management activities and/or areas where higher-resolution forest damage assessments are required.

- USFS 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.*)
- USFS 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.*)
- USFS 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.
- USFS operationally applied Landsat 7 Enhanced Thematic Mapper (ETM) and Landsat 8 OLI imagery to respond to 114 requests to map the location, extent, and severity of large wildfires amounting to more than 3.3 million acres in FY 2018. These rapid-response products support post-fire emergency stabilization/hazard mitigation activities conducted by Forest Service Burned Area Emergency Response (BAER) teams. (See *https://fsapps.nwcg.gov/baer/.*)
- USFS operationally applied Landsat 7 ETM and Landsat 8 OLI imagery to respond to map and estimate post-fire basal area loss and canopy cover loss for 191 large wildfires totaling nearly 4.2 million acres in FY 2018. These products support forest restoration planning management activities and efficient use of resources to support those activities. (See *https://fsapps.nwcg.gov/ravg/.*)
- USFS continued to operationally 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 2018 included the completion of an additional 832 fires, increasing the extent of historical MTBS data records to include 21,673 fires

covering more than 162 million acres of burned lands. (See *https://www.mtbs.gov*.)

- USFS 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 active fire detection algorithm, refine as needed, and provide output products to support USFS operational fire support activities. FY 2018 efforts also included advancements on extending the Landsat 8 algorithm to support the development of an active fire detection algorithm for Sentinel 2A/2B.
- USFS continued technology transfer activities between the USFS and Ames Research Center regarding Unmanned Aircraft Systems (UAS) and related technologies under the auspices of the NASA-USFS Wildfire Research Applications Partnership and a USFS-NASA interagency agreement. (See *http://geo.arc.nasa.gov/sge/WRAP/index.html*.) The effort also included the transfer and implementation of relevant information and NASA-developed technologies to support crewed and uncrewed airborne remote sensing activities in the USFS through the Tactical Fire Remote Sensing Advisory Committee (TFRSAC).
- USFS used imagery from Landsat 8 OLI and NAIP to initiate, complete, and update mid-level vegetation-mapping products for national forest lands and adjacent land areas throughout the country. Mapped areas included five National Forests encompassing more than eight million acres.
- USFS successfully completed the Tree Canopy Cover (TCC) data for 2016 updates for the continental United States using imagery from Landsat 8 OLI and NAIP as part of the Multi-Resolution Land Characteristics Consortium (MRLC) National Land Cover Database (NLCD) 2016.
- USFS 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*.)

- USFS continued progression toward a comprehensive and consistent land-cover/land-use monitoring system, the Landscape Change Monitoring System (LCMS), for the continental United States. LCMS utilized 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 development of an annual CONUS change product spanning 1984 to 2017. This effort is being conducted in collaboration with several Federal and academic partners. (See *http://larse.forestry.oregonstate.edu/lcms-landscape-change-monitoring-system* and *http://landsat.gsfc.nasa.gov/?p=10868*.)
- USFS continued to develop and refine standards and practices for integrating light detection and ranging (lidar) into forest and resource management (e.g., defining acquisition specifications, data-quality assessment, analysis/modeling procedures for forest parameters, etc.).
- USFS continued to expand USFS involvement in the USGS 3D Elevation Program to ensure consistent acquisition specifications and to minimize redundant collections by partnering with other state and Federal entities on data acquisitions.
- USFS 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 1-PB 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) staff continued to utilize CONUS and outside CONUS (OCONUS) 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.
- FIA continues to use NASA Goddard's Lidar, Hyperspectral, and Thermal Imager (G-LiHT) data with NAIP imagery in Florida to assess and monitor post-hurricane damage to coastal mangroves. Additionally, FIA works

with NASA scientists to use G-LiHT data to support forest inventory of interior Alaska.

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, provide geospatial data products for decision support to assess the flooding from Hurricanes Florence and Michael, and implement a survey-based geospatial imputation process. Additionally, NASS published papers describing operational agricultural flood monitoring with Sentinel-1 Synthetic Aperture Radar (SAR) and an evaluation of Sentinel-1A C-band SAR for citrus crop classification in Florida.

NASS used Landsat imagery, digital NAIP imagery, and other remotely sensed inputs for the contiguous United States and Puerto Rico to select the yearly area-based samples for the June Area Survey and the 2017 Census of Agriculture. 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 were derived from the Cropland Data Layer (CDL) for all market-sensitive crops and states. 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 2017 crop season via the USDA Geospatial Data Gateway and the CropScape data-visualization 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, GIS software, or high-end computers. This information can be used for addressing issues related to agricultural sustainability, land-cover monitoring, biodiversity, and extreme events such as flooding, drought, and hailstorm assessment.

NASS continued to utilize a new geospatial CDL-based automated stratification method for area sampling frame operations, resulting in ten updated state area frames built at reduced cost with improved objectivity, efficiency, and a 29 percent improvement in accuracy. The CDL data are used as the basis for the objective stratification of NASS area frame primary sampling units rather than visual interpretation of aerial photography or satellite data.

The CDL data and the CropScape Web application were used for the first time for June Area Survey imputation. The CDL data, which has 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 readily available tool and CDL data are used operationally to help NASS statisticians estimate acreage information missing from nonrespondent and inaccessible farmers in the editing and imputation process.

Geospatial decision support data products were delivered for rapid hurricane responses, including Florence and Michael assessments of flooding 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 posted on *https://www.nass.usda.gov/Research_and_Science/Disaster-Analysis/*. The Sentinel-1 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 FEMA usage.

NASS utilized NASA MODIS NDVI and Land Surface Temperature (LST) products for modeling corn and soybean yield indications over the 12 largest production states. In 2018, six new states were added to the corn yield program, providing coverage of up to 80 percent of U.S. corn production. 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 data and 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 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

The Rural Development Act of 1972, Section 302, directed the Secretary of Agriculture to put in place a land inventory and monitoring program that would, among other things, study and survey damage from soil erosion and sedimentation; floodplain identification and use; land-use change; and potential environmental damages resulting from the misuse of soil, water, and related natural resources. This program, which became the National Resources Inventory (NRI), results in the publication of a land inventory report at not less than five-year intervals on the condition of the Nation's soil, water, and related natural resources. In FY 2018, through an interagency agreement, NRCS used the Farm Service Agency's Aerial Photography Field Office to acquire high-resolution aerial photography (4-inch ground-resolving distance) and scans of over 70,500 sites in the contiguous United States, 470 sites in Puerto Rico and the U.S. Virgin Islands, and 340 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 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), NRCS holds title to 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 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 2017, NRCS continued the pilot project and used the USDA Small Area Aerial Photography Contract to acquire imagery for monitoring purposes. The collection was divided into 1) 24,679 high-resolution, natural-color negative film aerial photos and (2) 582,161 acres of direct digital, 15-centimeter-resolution, 4-band, orthorectified imagery in Alabama, Arkansas, Illinois, Indiana, Kentucky, North Carolina, New Hampshire, Virginia, and West Virginia. 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 during leaf-on time periods during the summer months. This dataset is the foundation layer for geospatial data used in USDA offices and our cooperators. NRCS; USFS; USGS-DOI; and 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 one-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/technical/cp/*), 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/*. NAIP is collected on a two- to three-year cycle for CONUS. In FY 2018, NAIP collected 25 states' worth of imagery. All were

collected at 0.6 meter and in four multispectral bands (Natural Color and CIR). NAIP collects all areas of the United States, including agricultural land, public lands (Federal, state, and local), and urban areas.

Satellite Imagery

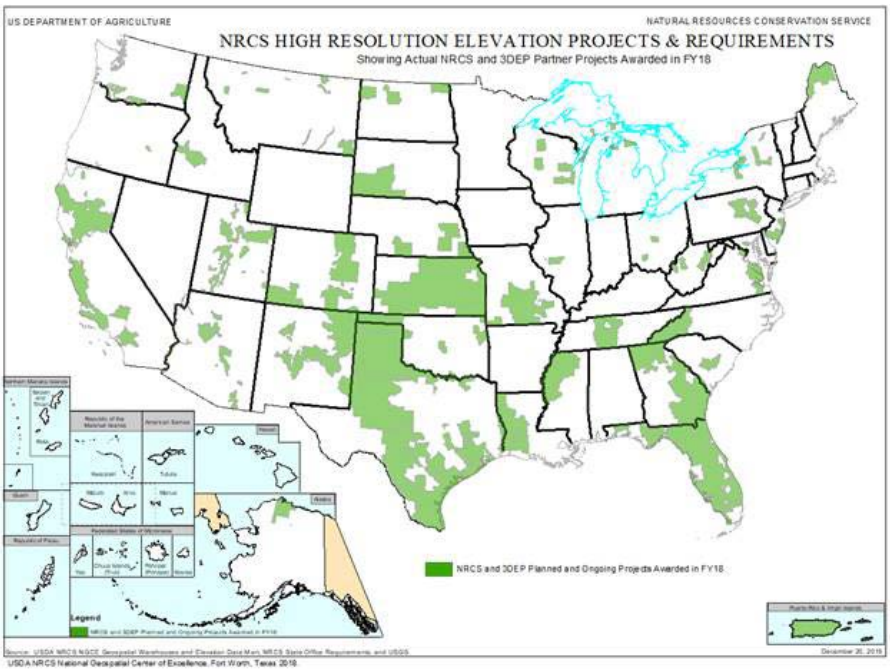
NRCS responds to geospatial imagery needs from all states and territories, including Puerto Rico, the U.S. Virgin Islands, Guam, the Commonwealth of the Northern Mariana Islands, American Samoa, and parts of Micronesia. NRCS requires high-resolution imagery at one meter or higher for most agency programs. Acquisition of imagery in non-CONUS areas is challenging because of remoteness and weather. NRCS uses satellite imagery from the DigitalGlobe EnhancedView Web Hosting Service (*https://evwhs.digitalglobe.com*) and purchases imagery from commercial sources for areas such as these and over-restricted airspace. DigitalGlobe imagery is also used for pre- and post-event disaster response and in cases where other imagery is outdated.

Elevation

NRCS has national requirements for high-quality elevation data, and the agency has a national strategy to acquire, integrate, and deliver high-quality digital elevation data that meet the agency's geospatial requirements. High-quality digital elevation data support the agency's business activities by improving employee effectiveness and efficiency in providing assistance to our customers.

NRCS participates in the USGS 3D Elevation Program (3DEP) to acquire high-quality 3D elevation data through remote sensing. (See *https://nationalmap.gov/3DEP/*.)

Elevation data are essential to a broad range of applications, including the design, implementation, and management of natural resources conservation practices; agriculture; precision farming; engineering; forest resources management; wildlife and habitat management; the determination of highly erodible lands; flood risk management; resource assessment; water supply and quality; and other business uses. This map depicts areas of actual lidar topographic acquisition projects that NRCS and 3DEP partners awarded in FY 2018. This area represents 583,427 square miles.



In FY 2018, 3DEP and its partners funded data acquisition for 16 percent of the Nation's area, resulting in a cumulative total of 53 percent of the Nation with 3DEP-quality data available or in progress. 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

NRCS utilizes signals broadcast from the GPS constellation of satellites to provide Positioning, Navigation, and Timing (PNT) services that support the NRCS mission of "Helping People Help the Land."

Employees of NRCS, located in over 2,000 Field Service Centers across the country, performed the following activities while using Space Based GPS PNT services in FY 2018:

- NRCS technical specialists and contractors used GPS as an aid for the collection of NRI information in 49 states on 2,350 sample areas known as area segments. In addition, the NRI collected data in 2018 for the

Bureau of Land Management on 1,000 area segments located on Federal land in 13 states. Most area segments contain three individual sample points. Each sample point represents a physical location on Earth's surface. NRCS and contract personnel used GPS to navigate to two of the three sample points and perform location validation upon arrival at the points. Accurate navigation to sample sites was essential for statistically valid data collection. Results of the data collection were analyzed and utilized to produce the "NRI Rangeland Resource Assessment" report as well as the "NRI Pastureland Assessment Report." Both documents were released in June 2018. Please see *https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/* for further information.

- The National Resources Inventory contracts the collection of aerial imagery on nearly 72,000 area segments each year. NRCS analysts housed in the three Remote Sensing Labs require consistently accurate location of the segments captured in the imagery. Repeated collection of data from accurately located area segments is used for trend analysis and is published in the NRI reports that support the 1976 Resource Conservation and Recovery Act. Use of space-based GPS and GPS corrections enables contractors to collect in-flight data for precision registration of images. Please see *https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/* for further information.
- Multiple NRCS states utilize GPS Space Based PNT services to navigate to and document the condition of conservation easements under the authority of the Agricultural Conservation Easement Program (ACEP). The ACEP provides financial and technical assistance to help conserve agricultural lands and wetlands and their related benefits. The ACEP, preceded by the Wetlands Reserve and other conservation easement programs, is funded through the current Farm Bill. Iowa, Kansas, and Vermont are among the states utilizing GPS and GNSS 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. Aerial

imagery was flown over segments, and the acquiring aircraft utilized Space Based PNT to collect image registration information. Periodic on-ground and airborne monitoring was used to assess the performance of the easements and to ensure that the easements conformed to the terms of the easement contracts. Private-sector Registered Land Surveyors used survey-grade GPS/GNSS equipment to establish and record boundaries of new agricultural easements and validate the boundaries of existing easements.

- NRCS soil scientists used Space Based GPS PNT to routinely navigate to soil-sampling sites to conduct follow-up investigation and to provide soil survey technical services to farm and ranch operators.
- The NRCS Water and Climate Center utilized Space Based GPS PNT to map locations of instrumentation and provide timing for telemetry signals. The coordination and delivery of data from 867 Snow Survey Telemetry (SNOTEL) stations and 226 Soil Climate (SCAN) stations require nanosecond precision that timing signals from GPS 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. Most of the stations utilizing Iridium are in Alaska.
- In FY 2018, 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. The plan maps are used by farm and ranch owner/operators to choose conservation practices that address the identified concerns. GPS was also used to verify measurements and document installed practices for contract cost-sharing payments.

Bryan and Chelsea Phipps have worked on conservation planning on their ranch with Sue Fitzgerald, NRCS district conservationist, in Jordan, Montana. Increased soil cover leads to cooler soil temperatures. Please see *https://www.arcgis.com/apps/Cascade/index.html?appid=f5fa1f4046b64640ae31eb69db5f1071* for additional information. (Photos courtesy of USDA NRCS)

- NRCS engineers utilized Space Based GPS PNT to perform detailed topographic surveys of farms 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 conservation practice and structural construction projects.
- During FY 2018, NRCS-California assisted Napa, Sonoma, Ventura, and Santa Barbara counties in evaluating the erosion hazards associated with the Thomas and Tubbs Fires. NRCS visited hundreds of sites, meeting with landowners and reviewing areas of concern. During the typical site visit, NRCS often used Space Based GPS PNT to mark coordinates that could later be loaded into GIS to produce maps for further analysis.

Risk Management Agency

The USDA's Risk Management Agency (RMA), created 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 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 hurricanes and fires. In 2018, RMA used remote sensing data, such as Landsat, Sentinel-2, Disaster Monitoring Constellation (DMC), MODIS, and high-resolution aerial and satellite imagery. 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 on a daily basis 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 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 Mathematics 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), 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 2018, 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 received over 1,800 observing proposals, the most for any observatory on the ground or in space. Early in FY 2019, for the first time, ALMA will make observations with all 66 antennas. 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 continues 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.

Construction of the NSF's Daniel K. Inouye Solar Telescope (DKIST) continued through FY 2018. DKIST is the result of a 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. When completed in 2020, DKIST will 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 89 percent complete and is both on budget and on schedule. In FY 2018, the sixth of eight Level-1 milestones was achieved with the completion of the telescope mount assembly (TMA). Also in FY 2018, the primary mirror (M1) and the M1 Cell Assembly were successfully transported to the DKIST site on Maui. The M1 Cell Assembly successfully underwent site acceptance testing. The M1 was integrated into the Cell Assembly and the entire package installed on the TMA for initial alignment. In early FY 2019, the project entered the critical Integration, Testing and Commissioning (IT&C) phase of construction, which will continue through the remainder of the project.

The National Solar Observatory (NSO) is the lead organization for the construction of DKIST. NSO will also operate the facility under a ten-year cooperative agreement. Funding for DKIST operations is in the final year of a five-year ramp to a steady-state level of approximately $16.5 million per year for FY 2019. NSO is currently building a new Data Center at its headquarters in Boulder, Colorado. This Data Center will process the ten to 12 terabytes of data per day expected from DKIST.

The importance of the potential impacts of space weather on the Nation's critical infrastructure has raised the level of awareness of space weather within the Federal Government. 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. In FY 2016, the NSF received a one-time increase of $2.5 million to refurbish GONG and make it operationally robust. Refurbishment activities for GONG continued through FY 2018. 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 2018, with realized risks remaining well within the originally assigned cost and schedule contingencies. Construction is over 62 percent complete. Major components are being shipped and will arrive at the summit soon, and "first light" is on schedule for 2020. After two years of commissioning to tune all of the complex interrelated operating systems, full science observing will start on October 1, 2022. 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, the NSF and the Department of Energy (DOE), expect this survey to generate 30–40 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 will support installation and commissioning together. Operations support has been requested from both agencies and will be augmented by negotiated non-Federal and international contributions. The NSF awarded initial pre-operations ramp-up support in FY 2018, and activity begins in FY 2019.

In FY 2018, AST's Mid-Scale Innovations Program (MSIP) supported 18 programs, with five-year project costs in the range of $3–10 million. There were numerous new projects awarded funding in FY 2018: The Keck All-Sky Precision Adaptive Optics system (KAPA) for use at the two Keck Observatory telescopes on Mauna Kea, Hawaii; the Multiple Mirror Telescope (MMT) Adaptive optics exoPlanet characterization System (MAPS), to be used at the MMT Observatory on Mt. Hopkins, Arizona; the Hydrogen Epoch of Reionization Array (HERA), for observations with the MSIP-funded low-frequency radio telescope array (240 14-meter antennas) in the Karoo Desert of South Africa, to observe the 21-centimeter emission signal of neutral hydrogen from the Epoch of Reionization in the early universe; Large Lenslet Array Magellan Spectrograph (LLAMAS), a facility integral field spectrograph for the Magellan Telescopes in Chile; Background Imaging of Cosmic Extragalactic Polarization (BICEP) Array Stage 3, a program, in collaboration with the Office of Polar Programs, to develop and observe CMB polarization at the South Pole with new telescope instrumentation; the Deep Synoptic Array (DSA), a Fast Radio Burst (FRB) localization machine consisting of 110 five-meter radio antennas to be built at the Owens Valley Radio Observatory in Central California; the Advanced Cryogenic L-band Phased Array Camera for Arecibo (ALPACA), for the Arecibo Telescope in Puerto Rico; GBT Metrology, a program for correcting surface deformations at the Green Bank Telescope in West Virginia, to support high-resolution three-millimeter molecular

imaging for the U.S. community; and operations support for the Long Wavelength Array (LWA) in New Mexico, in exchange for observing opportunities for the general astronomical public at this unique observatory.

Active MSIP awards from previous years included the Cosmic Large Angular Scale Survey (CLASS), a pair of telescopes being built at 5,200 meters (17,000 feet) on Cerro Toco near the ALMA site on the Atacama Plateau in Chile, designed to measure so-called "B-mode" polarization of the cosmic microwave background (CMB, the radiation at microwave wavelengths that is a remnant of the Big Bang); TolTech, a 3,000-pixel millimeter-wavelength camera for observing our galaxy and distant dusty galaxies, to be installed on the Large Millimeter Telescope in Mexico; and the Subaru Measurement of Images and Redshifts (SuMIRE), a camera and observing program developed by Princeton University for use on the Japanese Subaru Telescope on Mauna Kea in Hawaii to conduct a very deep optical survey of distant galaxies.

Other active MSIP programs supported in FY 2018 included the Zwicky Transient Facility (ZTF), a telescope/camera combination at Mount Palomar in California dedicated to high-cadence optical surveys and a pathfinder for the LSST; the Atacama Cosmology Telescope (ACT), a six-meter-diameter millimeter-wave telescope; and POLARBEAR, a 3.5-meter-diameter millimeter telescope. The last two are both, like CLASS, sited on Cerro Toco and are designed to measure minute variations in the intensity and polarization of the CMB. POLARBEAR is funded in partnership with the Simons Foundation. Also ongoing is an award for the Event Horizon Telescope (EHT), designed to measure, at extremely high resolution, radio emissions originating from the near environs of the black hole at the center of the Milky Way Galaxy.

MSIP also provided the U.S. astronomical community with observing time at the Center for High Angular Resolution Astronomy (CHARA) optical interferometer on Mount Wilson in California and at the Las Cumbres Observatory, a network of 18 optical telescopes at eight sites around the world working together as a single instrument.

Damage to the Arecibo Observatory (AO) resulting from Hurricane Maria, which hit the island of Puerto Rico in September 2017, was assessed and partially repaired during FY 2018. The observatory was closed for a short time but has since

resumed operations, 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. FY 2018 also saw a change in management for Arecibo to a consortium led by the University of Central Florida, which will allow the NSF to reduce its contribution toward Arecibo's operating costs from $8 million to $2 million by FY 2022, with the shortfall to be made up by the consortium partners. NSF support for AO was shared between AST and the Division of Atmospheric and Geospace Sciences in the GEO Directorate.

Division of Physics

The Division of Physics (PHY) continued to operate its Laser Interferometer Gravitational-Wave Observatory (LIGO), which underwent commissioning work during this calendar year in preparation for the third observational run to be started in April 2019.

Complementing LIGO, the Division of Physics, in partnership with AST, continued its funding of a Physics Frontiers Center for the study of gravitational radiation, called the North American Nanohertz Observatory for Gravitational Waves (NANOGrav). NANOGrav uses large radio telescopes to study the arriving clocklike signals from over 50 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 2018, the National Science and Technology Council (NSTC) reorganized the Space Weather Operations, Research, and Mitigation (SWORM) activity as a Working Group under the Space Weather, Security, and Hazards (SWSH) subcommittee within the Committee for Homeland and National Security (CHNS). The Space Weather Action plan, 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 develop models, observation systems, technologies, and approaches that inform and enhance national preparedness for the effects of space weather events." 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 NSTC efforts to revise and update the National Space Weather Strategy and Action Plan. In addition, NSF/AGS has a leading role in the efforts to improve the initial space weather benchmarks that were published in FY 2017. This effort has been focused on developing a process for obtaining worldwide community input. NSF/AGS also led an action (Goal 5.5.1 from the action plan) to identify space weather research priorities, including obtaining input from the scientific community via an RFI. A report documenting these priorities was submitted to the SWORM for approval.

The Geospace Section (GS) within AGS supported a wide variety of research programs in space science in FY 2018. 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 2018 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 2018, the GS continued to support the hires resulting from the most recent competition.

In FY 2018, the GS continued to support its program for CubeSat-based small-satellite science missions for geospace and atmospheric research and education. During FY 2018, one project continued to operate successfully in space and one new mission was launched. The analysis of high-quality observations from many of the previous missions continued to deliver scientific findings and results throughout FY 2018, including an article in *Nature* addressing the origin of electrons in the inner zone of Earth's radiation belts. In addition to the active projects, the GS section solicited new CubeSat mission proposals. Evaluation of these proposals was conducted, and awards are expected to be made early in FY 2019.

In FY 2018, 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 2018, 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 2017 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 2017, 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 awarded a five-year cooperative agreement to a consortium led by the University of Central Florida to operate the radar facility at Arecibo. In addition to the cooperative agreement award, the NSF has made an initial award of $2 million to repair damages caused by Hurricane Maria.

In FY 2018, 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. Shortly thereafter, data became available from the three payloads: the special space-based GPS radio occultation (RO) receivers, the so-called Tiny Ionosphere Photometers, and the Tri-Band Beacons. These data have been provided freely to the world scientific community.

COSMIC radio occultation data have been assimilated at many operational weather prediction centers, including the U.S. National Centers for Environmental Prediction (NCEP), the European Centre for Medium-Range Weather Forecasts (ECMWF), Météo France, the United Kingdom's Met Office, the Meteorological Service of Canada, Taiwan's Central Weather Bureau, and others. All of these centers have reported that RO data had a significant positive impact on numerical weather forecasts. In ionospheric studies, COSMIC RO data accelerated the development of physical models for space weather prediction by providing dense, accurate, and global electron-density measurements used for model testing and initialization, including the response of the global ionosphere to the impact of solar storms.

During FY 2018, only one COSMIC satellite was still reporting (well beyond the expected three-year life span) and produced about 250 occultations per day. The reduction in COSMIC coverage has been somewhat mitigated through the use of missions of opportunity, including the Korean Kompsat5 satellite, and UCAR is working with NOAA to obtain these data in near-real time. Approximately 90 percent of real-time processed COSMIC data are available for the users and operational weather forecasting centers within three hours. COSMIC supported more than 1,100 registered users from 52 countries. In collaboration with UCAR's Unidata, COSMIC soundings have been provided in real time to support the university community. UCAR also reprocessed data to provide consistent records for the duration of the mission and produced post-processed and reprocessed data from several GPS radio occultation (GPSRO) missions of opportunity. The NSF and NASA are jointly funding the COSMIC mission for the duration of its expected life span.

The NSF continued to collaborate with NOAA, the USAF, Taiwan, and UCAR to ensure the success of the follow-on COSMIC-2 mission. COSMIC-2 now consists of a six-satellite constellation to be launched into low-inclination orbits to provide dense coverage of the tropics. (A second polar constellation was planned but has now been cancelled.)

Office of Polar Programs

For FY 2018, 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 ten-meter off-axis radio South Pole Telescope (SPT); the battery of five small-aperture (50-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. The High Elevation Antarctic Terahertz (HEAT) robotic telescope, deployed since 2011 at the highest point of the Eastern Antarctic Plateau (Ridge A), has completed successful operation through 2017;

however, its removal from the Antarctic Plateau was delayed until January 2019. Scientific data collected through the lifetime of this project are now published, and all observational data are shared with the scientific community.

The SPT continued observations with the new, third-generation receiver SPT-3G, which has wide-field optics to measure the CMB polarization at high sensitivity. 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 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. In 2018, the SPT-3G's focal plane was ungraded to 16,000 detectors. Recent SPT results for delensing the CMB polarization signal from gravitational effects of galaxy clusters are helping with better understanding of foregrounds at the degree-scale anisotropies in the CMB.

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 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 eight 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 ten petaelectronvolts (PeV). The NSF has recently funded a moderate upgrade of

the detector, adding seven new strings to the existing six-string DeepCore array. This will boost significantly the detector's performance at the 5- to 10-GeV energy scale, yielding over an order of magnitude more statistics than current samples and enabling the world's best measurement of the tau neutrino. The upgrade will lead to the most stringent testing of unitarity in the tau sector of the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix that describes all known neutrino oscillation behavior. Any deviations from unitarity would be evidence for new physics.

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 PeV 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.

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. Data gathered by the NSF's IceCube Neutrino Observatory at the Foundation's Amundsen-Scott South Pole Station in Antarctica are helping to answer a more-than-century-old riddle about the origins of high-energy cosmic rays.

The group of international researchers traced a path of the single neutrino detected by IceCube on September 22, 2017, to a previously known but little-studied blazar, TXS 0506+056, 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 exploration of scientific frontiers has already changed and expanded understanding of the universe.

"The era of multi-messenger astrophysics is here," said NSF Director France Córdova in the NSF's Press Release 18-050 (July 2018). "Each messenger—from electromagnetic radiation, gravitational waves and now neutrinos—gives us a more complete understanding of the universe, and important new insights into the most powerful objects and events in the sky. Such breakthroughs are only possible through a long-term commitment to fundamental research and investment in superb research facilities."

The NSF's Division of Polar Programs also supports NASA's Long Duration Balloon 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.

Department of State

DOS

The Department of State (DOS) carries out diplomatic and public diplomacy efforts to strengthen American 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 this mission 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.

Bilateral Dialogues

The United States held productive and frank discussions with Japan on Space Policy Directives 1–3 and the National Strategy for Space at the fifth Comprehensive Dialogue held in Tokyo on July 20, 2018. Japan welcomed an invitation from NASA to participate in its lunar space exploration program, including the lunar orbiting platform known as Gateway. Japan also expressed support for expanding commercial activity in low-Earth orbit to include the International Space Station. Scott Pace, Executive Secretary for National Space Council (NSC), and Bill Liquori, Director of Space Policy at NSC, cochaired the meeting for the United States. Ambassador Kansuke Nagaoka, Deputy Assistant Minister at Japan's Ministry of Foreign Affairs (MoFA), and Shuzo Takada, Director General for the Cabinet-Level National Space Policy Office, cochaired the meeting for Japan. OES/

SAT led discussions pertaining to the United Nations (UN) Committee on the Peaceful Uses of Outer Space (COPUOS), space resource utilization, cooperation with other spacefaring nations, Global Navigation Satellite Systems (GNSS), and space weather. The dialogue emphasized a whole-of-government approach to civil, commercial, and national security space activities and cooperation.

Another important bilateral space dialogue that the Department of State facilitated during 2018 was with the European Commission (EC), which has a space agenda that continues to grow in both breadth and depth. On January 18, 2018, the Department hosted in Washington, DC, the ninth meeting of the U.S.–EU Dialogue on Space Cooperation to move forward this important dialogue on security and civil space activities between the two sides. More than 50 officials from both sides attended the meeting, including representation from more than ten U.S. Federal agencies. The U.S. side was led by officials from two State Department Bureaus: Oceans, Environment and Science (OES) and Arms Control, Verification and Compliance (AVC). The European side was led by the Special Envoy on Space from the European External Action Service (EEAS) and the EC's Directorate General for Internal Market, Industry, Entrepreneurship and Small Medium Enterprise (DG-GROW). The civil dimension of the meeting was dominated by detailed discussions on U.S.–EU cooperation on two major European space systems: the Galileo program on Global Navigation Satellite System (GNSS) and the Copernicus Earth observation program. Both programs continue to receive growing financial investments from the European Commission. Most important, they continue to offer unique opportunities for transatlantic collaboration between the United States and the European Commission. For instance, Europe's Copernicus constellation of Sentinel satellites provides free access to satellite data for FEMA's emergency response during the 2018 Atlantic hurricane season and to the U.S. Coast Guard for its operational responsibilities to monitor and track icebergs threatening the safety of U.S. and international shipping in the North Atlantic. One of the outcomes of this annual bilateral meeting on space is a short work plan, with specific action items which grow in number and breadth, bringing notable value for both civil and security needs of the U.S.-EU transatlantic space agenda. The next meeting of this dialogue is planned for January 2019 and will be hosted by the European Commission in Brussels.

Working-level discussions with the EU on GNSS also continued in FY 2018 through working groups formed by the 2004 U.S.-EU GPS-Galileo Cooperation Agreement, administered for the United States by State-OES/SAT. The working group on next-generation GNSS applications and its three subgroups, Service Evolution, Resiliency, and Service Provision Coordination, met in April 2018. The working group on trade and civil applications also met in July 2018. In FY 2018, the United States also held discussions with the EU on potential U.S. access to the Galileo encrypted Public Regulated Service (PRS), with an emphasis on increased resiliency.

U.S. bilateral space cooperation in the Asia-Pacific region was very active and successful in 2018. From April 16 to 18, in collaboration with the Space Foundation, OES/SAT implemented and conducted the first Asia-Pacific panel discussion on space policy and international cooperation at the annual Space Symposium with four nations: Japan, South Korea, Vietnam, and Thailand. The forum accomplished three central objectives: 1) provided the U.S. space community with an understanding of these countries' space policy decision-making process and key goals, 2) provided U.S. space industries and agencies unique access to policy makers in these key spacefaring nations, and 3) raised the importance of international space collaboration in the region.

The third U.S.-Vietnam Civil Maritime Domain Awareness (CMDA) workshop was held from May 3 to 10 to lay the groundwork for the creation of a space-based data collection center, the first of its kind in Southeast Asia. With the commitment of the government of Vietnam and technical assistance from the United States, the Center will act as the central data warehouse and analytic center for supporting Vietnam's whole government decision-making process, which will address the safety, security, economy, and environment of the country.

During the week of October 31, on the margins of the 25th Asia Pacific Regional Space Agency Forum in Singapore, Boeing sponsored a three-day workshop for the Asia-Pacific "space generation" young professionals, following two years of collaborative work with the Department's Office of Space and Advanced Technology. Over 100 students and young professionals from 23 nations across the Pacific participated in the workshop focusing on emerging space issues such as the rise of small satellites and how the Internet of Things will shape the area's economy.

In November 2017, the State Department led a U.S. delegation to Beijing for the third bilateral U.S.-China Civil Space Dialogue. This included discussions on Earth and space science cooperation, space exploration, space debris, and the long-term sustainability of outer space. The result of this dialogue led to a follow-up Expert Exchange on Space Flight Safety, which was held in April 2018 on the margins of the Space Symposium in Colorado Springs.

The State Department continued to lead productive bilateral GNSS meetings with China in FY 2018, including a plenary-level dialogue and meetings of the three subgroups—Compatibility and Interoperability, Satellite Based Augmentation Systems, and Civil Service Provision—which took place in May 2018. Prior to that, in November 2017, the United States and China signed a nonbinding Joint Statement on GNSS Compatibility and Interoperability, highlighting an agreement on signal designs that ensures compatibility and improved interoperability between GPS and the BeiDou Navigation Satellite System.

The United States held a bilateral GNSS and Space Weather Dialogue with the government of Canada in November 2017. OES/SAT chaired the meeting on the U.S. side, and the meeting focused on improving coordination on operational issues and increasing collaboration in specific areas of interest to both countries.

Multilateral Activities

In December 2017, State Department led the U.S. delegation to the 12th meeting of the International Committee on GNSS (ICG) in Kyoto, Japan. This meeting brought together more than 200 experts and government officials representing 20 countries and organizations to discuss GNSS service provision and use in a multilateral forum. The four working groups of the ICG include Systems, Signals and Services; Enhancement of GNSS Services Performance; Information Dissemination and Capacity Building; and Reference Frames, Timing and Applications. All four working groups met and developed four new recommendations that were adopted by the full ICG, with a focus on improving GNSS compatibility and interoperability as well as improving outreach to the user community.

In FY 2018, OES/SAT continued its long-standing efforts to lead the U.S. delegation to the United Nations Committee on the Peaceful Uses of Outer Space

(COPUOS) and supported its Legal Subcommittee (LSC) and Scientific and Technical Subcommittee (STSC). State also continued to lead the participation of both U.S. Government and private-industry participation in the Working Group on Long-Term Sustainability of Outer Space Activities (LTS). In 2018, the working group completed eight years of work that resulted in 21 voluntary guidelines for ensuring the long-term sustainability of outer space activities through best practices focused on enhancing the safety of space operations. The United States played a leading role in the development of these guidelines, which take into account the needs of governmental space programs and the growing commercial space industry. The United States will continue to report on the domestic implementation of these guidelines through COPUOS and encourages all spacefaring nations to do the same.

In June 2018, COPUOS celebrated the 50th anniversary of the first United Nations Conference on the Exploration and Peaceful Uses of Outer Space (UNISPACE+50), and the United States, led by DOS, made contributions to the agenda of this event as well as seven thematic priorities that will guide the work of the committee through 2030. Additionally, DOS continued co-leading an action team to develop a plan of activities to be approved in 2018, highlighting the importance of international cooperation in global space exploration efforts.

Science Envoy for Space

Under the State Department's Science Envoy Program, OES/SAT had the opportunity to manage several highly productive overseas trips for the Department's first Space Envoy, Charles Bolden, former NASA Administrator and former Space Shuttle commander and astronaut. In October 2018, OES/SAT scheduled a robust trip for the Space Envoy in the United Arab Emirates (UAE) and Jordan to promote space exploration and commercialization of space. In Abu Dhabi and Dubai, Envoy Bolden participated in public events chosen to promote U.S. leadership in space, including speaking engagements at multiple primary schools; two public film screenings of *Above and Beyond: NASA's Journey to Tomorrow*; participation in a Q&A session moderated by Alia Al-Mansoori, a teenage Emirati aspiring astronaut; a visit to the Mohammed bin Rashid Space Center to discuss the Mars

Mission; meetings with the Minister of Advanced Sciences and UAE's Youth Council; and multiple interviews. In Jordan, through OES/SAT coordination with Embassy Abu Dhabi's public relations officer, Envoy Bolden's delegation and four students who won an online contest camped in the desert in Wadi Rum. Envoy Bolden also attended a high-level dinner, whose participants included Princess Sumaya and prominent members of the Jordanian business and scientific community. Additionally, he gave the keynote address at the 2018 American Chamber MENA (Middle East North Africa) Regional Council Conference. He also engaged with over 750 students and faculty during three separate outreach events arranged by OES/SAT in coordination with the embassy's public diplomacy office. Toward the end of the fiscal year, OES/SAT continued to orchestrate other space exploration and STEM outreach trips for Envoy Bolden to Ethiopia and South Africa, as well as future countries to be announced.

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 National Nuclear Security Administration (NNSA), the DOE Office of Science (SC), and the DOE Office of Nuclear Energy (NE).

Mission Contributions Within the National Nuclear Security Administration

Planetary Defense: NNSA has 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 to develop a strategic framework for space protection, primarily focusing on satellites. The DAMIEN initiative developed the 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 five strategic goals. The two pertaining to NNSA include improving NEO modeling, predictions, and information integration and developing technologies for NEO deflection and disruption missions. The actions of these two strategic goals are being fulfilled by the Interagency Agreement regarding planetary defense between NNSA and NASA.

NASA leverages NNSA-unique engineering, scientific, and computing capabilities for analyzing asteroids and planetary defense scenarios. 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.

The NNSA-NASA interagency agreement involves collaborating to

- characterize the potentially hazardous asteroid target sets, define mission requirements, and identify capability gaps;
- examine 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;
- define additional development and system engineering requirements addressing technical gaps such as arming, fusing, and firing a deflection device;
- participate in Planetary Defense tabletop exercises and technical interchange meetings; and
- advise on risk-assessment analysis and the effectiveness of mitigation approaches.

Strategic Partnership Projects: NNSA supports Strategic Partnership Projects, funded by NASA, with the following capabilities:

- Providing metrology support with calibration on standards and measuring test equipment supporting metrology areas at NASA's White Sands Test Facility.
- Monitoring satellite visible-light sensor data for bolide occurrences worldwide and generating reports detailing bolide parameters.
- Modeling asteroid entry, airburst, and surface impact effects.
- Enabling joint exploration of sounding rocket technologies at NASA's test ranges.

Small Fission Power Systems: NASA recently employed NNSA assets to develop and test a prototypic reactor and power system that may enable NASA to potentially provide stationary surface power capability. A technology demonstration project, referred to as Kilowatt Reactor, using Stirling Technology, was completed in 2018 utilizing expertise from Los Alamos National Laboratory (LANL), the Y-12 National Security Complex, and the Nevada National Security Site to demonstrate heat transfer and conversion principles utilizing a subcritical experimental reactor as the basis for driving the nuclear reaction. This project

provided insight to NASA as to whether the reactor design concept is suitable for future flight development. NNSA retained the fissile material, which is available to perform a variety of radiation test object and nuclear data experiments supporting safety, security, and other NNSA missions.

Radioisotope Power Systems (RPS) Launch: NNSA and NASA work collaboratively during the preparation for and execution of the RPS launch at Kennedy Space Center (KSC).

- During the preparation phase, NNSA and NASA review and update procedures and conduct training, drills, and exercises with the state, tribal, and local emergency management organizations and agencies 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 stages technical specialists and sensors in the vicinity of the launch site to be prepared to respond immediately in the unlikely event of a launch anomaly. NNSA personnel would be assigned to the KSC Primary Agency Representative Management Group, the Radiological Control Center, and the Joint Information Center to provide real-time data assessment and risk-communication support to KSC and coordinate with the NNSA Consequence Management Home Team should an NNSA-led Federal Radiological Monitoring and Assessment Center be established offsite following a launch anomaly.

NASA's Environmental Continuous Air Monitors: NNSA maintains the Environmental Continuous Air Monitors (ECAMS) that NASA owns for deployment around the launch site in advance of a launch to provide indication of a release, should one occur. NASA has agreed to loan these sensors to NNSA for use 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 and 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—specifically 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 accomplish 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 2018, 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 the NASA mission, NASA researchers, SC program offices, and SC-sponsored scientists; 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 2018 include 1) the Large Plasma Device at the Basic Plasma Science Facility at the University of California, Los Angeles, which enables controlled studies of Alfvén waves that carry energy and momentum from the Sun to Earth and throughout the universe; 2) the Magnetic Reconnection Experiment at the Princeton Plasma Physics Laboratory, which permits 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 at the University of Wisconsin–Madison, which allow 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, established in 2012 in partnership with the Max Planck Society in Germany, which specifically explores the application of plasma science to solar and astrophysical problems and their connections to fusion science.

In addition, FES sponsored unmagnetized plasma and high-energy-density laboratory plasma research, focused on areas such as increased understanding of the role of dusty plasmas in planetary rings and interstellar media, understanding 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. Over the past three years, SC has been engaged in a number of strategic planning efforts, including an FES-sponsored a series of community-led research opportunities workshops to identify compelling scientific challenges at the frontiers of plasma physics and fusion science, which identified research opportunities for the next decade. Plasma science governing space weather, an area of broad mutual interest to NASA and FES, was highlighted in the workshops. Furthering the study of laboratory plasmas for growing our understanding of astrophysical plasma phenomena was also a focus. A number of these NASA-relevant research areas were supported as part of several FES funding-opportunity announcements for universities and DOE national laboratories in FY 2018.

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. 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 DOE 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 DOE and NASA defined NASA's responsibilities to include provision of power, data handling, and other services on the ISS, while DOE's responsibilities include experimental operations and data analysis. As of 2018, more than 100 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.

The Large Area Telescope (LAT), the primary instrument on NASA's FGST, is a particle physics detector in space 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 monitors the entire sky in high-energy gamma rays and enables searches for transient phenomena over a wide range of timescales. SC managed the LAT fabrication and now operates the LAT Instrument Science Operations Center. In 2018, the LAT published competitive limits on the evaporation of primordial black holes and limits on a dark-matter annihilation signal in electrons based on the very high statistics for cosmic-ray electrons in LAT data.

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. Final results describing the cosmological legacy of Planck were published in 2018 and provided the strongest constraints on parameters of the universe, including models of the early universe and large-scale structure. The results also include precision measurements of dark energy and the neutrino mass scale. 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.

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 2018, 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 (TCCON); these measurements are being used to

validate NASA's Orbiting Carbon Observatory-2 (OCO-2) satellite. SC's ARM user facility also supported the launch of dedicated radiosonde observations during satellite overpasses 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.

The SC TES activity supports the Next Generation Ecosystem Experiment (NGEE)-Arctic, which has collaborated with the NASA Arctic-Boreal Vulnerability Experiment (ABoVE) 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 (MOA) 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 Goddard's Lidar, Hyperspectral, and Thermal (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. An upgrade mutually beneficial to and jointly funded

by NSRL (NASA) and RHIC (SC) was the construction of the Electron Beam Ion Source (EBIS), supported by SC's Office of Nuclear Physics (NP), which expanded the range of ion species available for both radiological effects research and fundamental nuclear science; EBIS was fully commissioned in 2015. The "Extended EBIS" upgrade, initiated by BNL in 2016 with shared funding from SC and NASA and continued in FY 2018, benefits NSRL with increased ion beam intensities for gaseous elements, including light ions such as hydrogen and helium. Recently, the Galactic Cosmic Ray Simulator mode of operation at NSRL has been developed to provide many different ion beams in a short period of time. 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.

Lastly, electronics space-radiation effects testing that is necessary for mission assurance occurs at several DOE accelerator facilities, including BNL and the Lawrence Berkeley National Laboratory's 88-inch cyclotron. SC's NP and NASA are supporting the 88-inch cyclotron operations to accomplish their respective missions. SC and other stakeholders are initiating research and development that could lead to enhanced capabilities for radiation effects testing at the 88-inch cyclotron. 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* (available at *https://www.nap.edu/catalog/24993/testing-at-the-speed-of-light-the-state-of-us*), focused on a comprehensive assessment of the future needs of the electronics space-radiation effects testing program in the United States. Among other findings, the NAS report recommended the creation of a joint coordination body, to include DOE and NASA, which would "define the usage needs for parts radiation testing and assure the adequacy and viability of radiation test facilities out to 2030."

Capabilities Developed via DOE Office of Nuclear Energy Sponsorship

NE supports NASA's planetary science and human exploration programs by maintaining capabilities to develop, produce, and deliver radioisotope power

systems (RPSs) for Federal user agencies, such as NASA. The RPS infrastructure capabilities, funded by NASA and managed by NE, support NE's production of RPSs for current space mission applications. NE and its predecessors have provided RPSs that have safely enabled deep space exploration and national security missions for over five decades. The RPSs convert the heat from the natural radioactive decay of plutonium (Pu)-238 into electricity. RPSs reliably operate for decades under the harsh conditions encountered in deep space or on the surfaces of other planets.

In FY 2018, NE continued to support the next RPS-powered mission, Mars 2020, completing a number of major milestones. Early in the second quarter, LANL successfully manufactured 28 fueled clads, providing 20 flight-quality fueled clads for the Mars 2020 mission and eight spare fueled clads. Within this inventory, six fueled clads contained some of the newly produced plutonium-238 from Oak Ridge National Laboratory (ORNL), demonstrating DOE's progress to re-establish domestic Pu-238 production capabilities. Early in the third quarter, Aerojet Rocketdyne Holdings, Inc. (AR), successfully completed the fabrication of two Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) Flight Units. In the fourth quarter, the Idaho National Laboratory (INL), with the support of AR, developed power predictions for MMRTG Flight Units 2 and 3 to support the Mars 2020 Project in its flight unit selection. Also in the fourth quarter, INL completed fueling of the 16 graphite impact shell (GIS) assemblies required for the Mars 2020 mission. The GIS assemblies contain 20 new fueled clads recently manufactured at LANL for the Mars 2020 mission, along with 12 fueled clads from the existing inventory. Additionally, NE continued to work with Sandia National Laboratory to prepare the Mars 2020 Safety Analysis Report to support the Presidential Directive/National Security Council nuclear launch approval processes.

With NASA funding support, NE continues to invest in current RPS production infrastructure through an approach called constant-rate production (CRP). Beginning in FY 2018, 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

1. producing 1,500 grams of heat-source Pu-238 oxide annually by FY 2025 and
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 to the NASA mission of reducing the mission-specific cost for utilizing an RPS since the support for CRP would eliminate the costly, cyclical approach to stand-up and stand-down fuel production activities. DOE national laboratories have already demonstrated results toward achieving the CRP goals. Since 2015, ORNL has produced approximately 350 grams of heat-source plutonium-238 oxide over three campaigns at High Flux Isotope Reactor (HFIR) and initiated a fourth campaign in the fall of 2018 that is expected to provide 350 grams of material. In FY 2019, the plan is for production to ramp up to 400 grams of heat-source plutonium-238 oxide per year and, by 2024, that production will increase to 1.5 kilograms of material per year to meet future NASA mission needs. Efforts are under way to optimize the HFIR beryllium reflector for Pu-238 production and to certify the Advanced Test Reactor at INL for production in the early 2020s, utilizing a standard neptunium target. Additionally, LANL successfully manufactured 22 fueled clads in a 12-month period in support of the Mars 2020 mission, demonstrating the ability to sustain CRP fueled-clad goals into the future.

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 flight-worthy 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.

Finally, NE, through the DOE national laboratories, provides technical support for the Nuclear Thermal Propulsion (NTP) system development led and funded by NASA. In the fourth quarter of FY 2018, NASA's Marshall Space Flight Center provided funding to DOE/INL to continue efforts on NTP. NASA has renewed its efforts to design, develop, and deploy a nuclear thermal propulsion system to power crewed deep space missions by 2030, which has support from Congress. The collaborative effort, which also involves LANL, Oak Ridge National Laboratory, and Babcock and Wilcox Technologies, Inc., will involve new work for the Transient Reactor Test Facility to support NASA experimental-fuel needs and includes technical project oversight, ground-test trade studies, reactor conceptual design, fuel/fuel element fabrication technology development and testing, 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 that ended in 1972.

Smithsonian Institution

The Smithsonian Institution continued to contribute to national aerospace goals through a variety of activities in FY 2018. The Smithsonian Astrophysical Observatory (SAO) and the Harvard College Observatory jointly form the Center for Astrophysics | Harvard & Smithsonian (CfA) in Cambridge, Massachusetts. Through this organization, more than 300 scientists engage in a broad program of research in astronomy, astrophysics, Earth and space sciences, and science education during the year. The Smithsonian National Air and Space Museum (NASM) and the Smithsonian National Museum of Natural History (NMNH) in Washington, DC, also contributed to reaching national aerospace goals through research and education activities.

Three widely reported stories featured SAO astronomers in FY 2018. The first was the discovery of a population of intermediate-mass black holes by scientists using the Chandra X-ray Observatory among other facilities. (SAO runs the Chandra mission for NASA.) Black holes are among the most amazing and bizarre predictions of Einstein's theory of gravity, point-like in dimension but surrounded by imaginary edges ("event horizons") within which anything that ventures becomes lost forever to the rest of the universe. Despite being implacable sinks for matter and energy, the regions around black holes are often sources of powerful emissions that have allowed thousands of black holes to be discovered, most of them large, with more than a million solar-masses. The new paper has discovered, for the first time, a population that is only between hundreds to tens of thousands of solar-masses. The second widely reported item was the successful launch of the Parker Solar Probe, reported in *Nature*, which will "fly into the sun" to probe its upper atmosphere, the corona. SAO built the Solar Wind Electrons Alphas and Protons (SWEAP) experiment onboard. The third item is the measurement

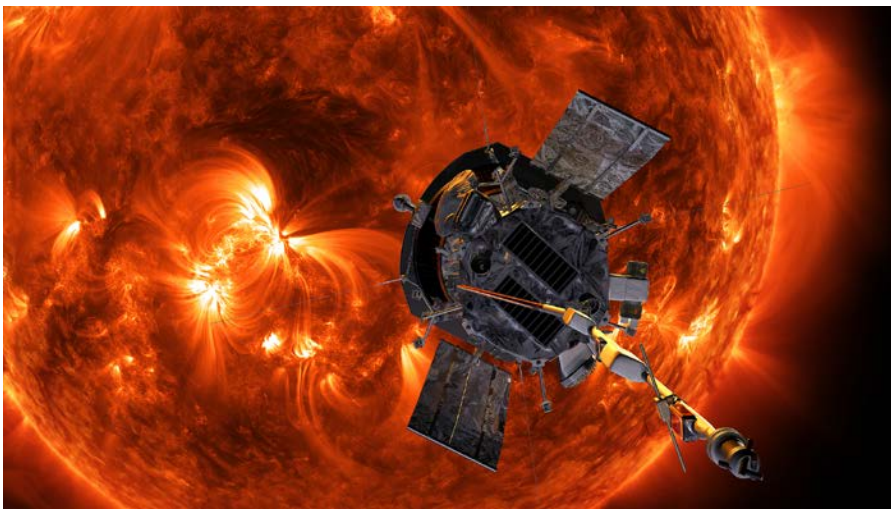


Illustration of the Parker Solar Probe approaching the Sun. (Image credit: NASA/Johns Hopkins Applied Physics Laboratory [APL]/Steve Gribben)

of 'Oumuamua—the mysterious, elongated, visiting interstellar asteroid—by the Infrared Array Camera (IRAC) on the Spitzer spacecraft; SAO scientists led the development of IRAC and its observations of 'Oumuamua.

The Chandra X-ray Observatory (a NASA "Great Observatory") is an orbiting telescope for precision x-ray astronomy for which SAO played a key design and development role. SAO also runs the Operations Control Center in Cambridge. Chandra, with its unrivaled ability to obtain high-resolution x-ray images, plays a pivotal role in the exploration of the universe, enabling astronomers to investigate phenomena as diverse as comets, black holes, supernova remnants, galaxy clusters, dark matter, and dark energy. Chandra operates at a high efficiency, carrying out observations for teams from all over the world with a high productivity rate averaging about 450 publications per year. In 2018, Chandra discoveries included nuclear outbursts in radio galaxies, a galaxy-scale fountain of gas pumped by a black hole, newborn stars without protoplanetary disks, and some exotic binary stars.

NASA's Spitzer Space Telescope, now in its 15th year of operation and 251 million kilometers away from Earth, 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 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

An artist's conception of 'Oumuamua, the first known interstellar object to visit the solar system. (Image credit: NASA/JPL)

Spitzer ran out of cryogens nearly ten years ago; IRAC has now been on continuously for a remarkable 1,100 days. In 2018, IRAC discoveries included dust in exoplanetary atmospheres, flares from the black hole at the center of the Milky Way Galaxy, and dramatic emissions from a spectacular gravitational wave source—a binary neutron star merger. (The gold on Earth is thought to be a product from these exotic mergers, which until now have never been directly detected.)

The Solar Dynamics Observatory 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 as "space weather" around Earth. SAO is a major partner in the Atmospheric Imaging Assembly (AIA)—a group of four telescopes that photograph the Sun in ten different wavelength bands, or colors, 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 better understanding of the physical processes in solar flares. During 2018, SAO scientists continued their involvement in other solar satellites, including Hinode and the Deep Space Climate Observer.

FY 2018 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 now been fabricated, and one has been polished and prepared for shipment to the site in Chile.

The Event Horizon Telescope (EHT) is a developing facility that unites telescopes around the world to study the event horizon of the supermassive black hole at the center of the Milky Way. SAO's Greenland Telescope is now a part of the EHT consortium. In 2018, the EHT team used the Submillimeter Array (SMA, jointly built and operated by the Smithsonian Astrophysical Observatory and the Academia Sinica Institute of Astronomy and Astrophysics), together with eight other facilities around the world, to examine the black hole and activity going on around it. SAO scientists are exploring the possibility of adding a space-based telescope to improve the spatial resolution of the EHT. SAO scientists also combined SMA observations of flaring of the black hole (produced as the black hole accretes material) with simultaneous measurements taken by the Chandra and Spitzer space telescopes. In separate research, SAO scientists used the SMA to probe an unexpected outburst in a newly forming star, thought to be due to accretion, and to analyze the structures of galaxies in the very early universe.

The Tropospheric Emissions: Monitoring Pollution (TEMPO) mission has made excellent progress in 2018 and is nearing completion of the instrument construction, with launch scheduled in 2019. 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 across the North American continent every daylight hour at high spatial resolution. SAO's Arcus mission was selected in 2017 by NASA to compete in a final down-select for the next Medium-Class Explorer (MIDEX) mission, and that selection is still under way. Arcus is a high-resolution x-ray grating spectrometer telescope mission. SAO is a team

member of a second competing MIDEX selection: SPHEREx, a telescope that will conduct four all-sky infrared spectral surveys. 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 pursues a wide variety of nationwide STEM education and outreach initiatives, many of which are 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 2018, 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 and nebulae, galaxies, exoplanets, and other astronomical phenomena. 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. "The Dynamic Sun," an exhibit conceived, designed, and built by SAO researchers, features a giant seven-by six-foot video wall intended to create a visceral impact and show visitors how an ever-changing Sun affects Earth. The "Dynamic Sun" at NASM in Washington, DC, continues to be seen by millions of visitors each year.

In FY 2018, NASM continued to educate and inspire the public through exhibits, research, and education programs, including discovery stations, lecture series, family educational events, STEM Webcasts, and intern training. The museum announced and continued preparations for the extensive seven-year project to revitalize the building's aging infrastructure and transform all exhibit spaces. The traveling exhibition "Destination Moon: The Apollo 11 Mission" brought the iconic Apollo 11 Command Module Columbia to three cities across the country: Houston, St. Louis, and Pittsburgh. The exhibition includes historic artifacts from the mission and a 3D interactive unit, based on high-resolution digital scans, that allows visitors to explore the Columbia inside and out. Seattle's Museum of Flight

will host the exhibition next year on the 50th anniversary of Apollo 11, and planning has begun for anniversary events and activities to be held at NASM on the National Mall. Work was completed on the book *Apollo to the Moon: A History in Fifty Objects* authored by NASM curator Teasel Muir-Harmony.

In 2018, the museum completed its four-year observance of the centenary of World War I. The program included a wide range of education and outreach programs, concerts, and a film series. The centerpiece of the NASM WWI centenary program was the exhibition "Artist Soldiers: Artistic Expression in the First World War," which featured rarely seen artworks created by soldiers in WWI. In July, the museum acquired the high-performance aircraft Oracle Challenger III. The aircraft was built with the latest technologies for aerobatics. Oracle Challenger III will be displayed in "We All Fly," a future exhibition dedicated to the many fields of general aviation. The museum provided new opportunities promoting STEM education. The She Can summer camp is a free program made available to low-income students in the DC metropolitan area. In this program, 6th- to 8th-grade girls participated in aviation-related activities, including flight lessons on a simulator, discovery flights, and indoor skydiving. Thirty teachers from across the country participated in the Teacher Innovator Institute, which invited educators to develop lessons for their classrooms based on the wide variety of resources the museum has to offer.

Staff members in NASM's Center for Earth and Planetary Studies (CEPS) continued to participate on the science teams of several spacecraft missions. Dr. John Grant is a Participating Scientist for the Mars Exploration Rover (MER) mission that is currently operating on Mars. He is a chair of the MER Science Operations Working Group, and in that capacity he leads day-to-day science planning for the Opportunity rover. In addition, he is cochair of the Mars 2020 Landing Site Steering Committee. CEPS staff are also on the science teams for the Mars Science Laboratory (MSL), the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) instrument on Mars Express, both the High Resolution Imaging Science Experiment (HiRISE) and Shallow Subsurface Radar (SHARAD) instruments on the Mars Reconnaissance Orbiter (MRO), InSight, the radar sounder on ESA's Jupiter Icy Moons Explorer (JUICE), the Lunar Reconnaissance Orbiter (LRO), Dawn, and the Europa Clipper. CEPS continued

its active research program in planetary and terrestrial geology and geophysics with research on such topics as comparative planetology; Martian aeolian, climate, and impact studies; lunar tectonics; planetary volcanism and cryovolcanism; and radar studies of Martian subsurface ice.

The Smithsonian National Museum of Natural History (NMNH) 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 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 on asteroids, 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 continues 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 remain actively engaged in spacecraft missions, with Tim McCoy serving as Co-Investigator on the OSIRIS-REx mission and Psyche missions. OSIRIS-REx has arrived at asteroid Bennu. In 2019, the spacecraft will sample the surface and return samples to Earth for study in 2023. McCoy 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 this year, 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 Web site.

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
* (through September 30, 2018)				
TOTAL	**1,828**	**163**	**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.

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				
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
*(through September 30, 2018)															
TOTAL	**1,586**	**3,072**	**10**	**8**	**107**	**284**	**1**	**1**	**270**	**62**	**8**	**4**	**2**	**1**	**1**

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.

Appendix B
Successful Launches to Orbit on U.S. Vehicles

October 1, 2017–September 30, 2018

Launch Date Spacecraft Name COSPAR* Designation Launch Vehicle	Mission Objectives	Apogee and Perigee (km), Period (min), Inclination to Equator (°)	Remarks
October 9, 2017 Iridium NEXT 3 2017-061A-H,JK Falcon 9 v1.2	Communications	626.9 610 97.02 86.6	Next generation expected to last to 2030.
October 11, 2017 EchoStar 105/SES 11 2017-063A Falcon 9 v1.2	Communications	35,799 35,787 1,436 0	SES will control the 24 C-band transponders; EchoStar the 24 Ku-band transponders.
October 15, 2017 NROL 52 2017-066A Atlas 5-421	Data Relay	35,802 35,786 1,436.10 4.9	
October 30, 2017 Koreasat 5A 2017-067A Falcon 9 v1.2	Communications	35,787 35,799 1,436 0	Carries 36 Ku-band transponders, providing Internet access, television broadcast, and other multimedia services in Korea, Japan, the Philippines, Guam, Southeast Asia, and South Asia.
October 31, 2017 6xSkySat/4xDove 2017-068A-F, J-L Minotaur-C	Optical Imaging	525 500 94.83 97.3	
November 12, 2017 Cygnus OA-8 2017-071A Antares 230	International Space Station	ISS	Cargo resupply.
November 18, 2017 JPSS 1/NOAA 20 2017-073A-E Delta 2-7920	Earth Science and Meteorology	818 528 97.4 97.6	First in NOAA's Joint Polar Satellite System. Calibrate over-the-horizon radars used by the Australian military and put Australia back into space. Compact atmospheric sensing nanosatellite from Massachusetts Institute of Technology that will measure temperature, water vapor, and cloud ice in the atmosphere for severe weather monitoring and the study of cyclone structure. Determine the best polymer for 3D printing future spacecraft. Monitor ionizing radiation effects in a memory integrated circuit. Became known as NOAA 20 on orbit.
December 15, 2017 Dragon 8.2/CRS-13 2017-080A Falcon 9 v1.2	International Space Station	ISS	Cargo resupply.
December 23, 2017 Iridium NEXT 4 2017-083A-H, JK Falcon 9 v1.2	Communications	625 609 97 86.7	
January 8, 2018 Zuma 018-001A Falcon 9 v1.2		n/a	Spacecraft lost after achieving low orbit.
January 12, 2018 NROL 47 Delta 4M+5,2	Radar imaging	1,057 1,047 106.2 106	

* U.N. Committee on Space Research

Appendix B (cont.)

Successful Launches to Orbit on U.S. Vehicles

October 1, 2017–September 30, 2018

Launch Date Spacecraft Name COSPAR* Designation Launch Vehicle	Mission Objectives	Apogee and Perigee (km), Period (min), Inclination to Equator (°)	Remarks
January 20, 2018 SBIRS GEO 4 2018-009A Atlas 5-411	Infrared Imaging	35,758 35,815 1,436.10 6.3	
January 31, 2018 Govsat 1 Falcon 9 v1.2	Communications	35,766 35,807 1,436.10 0	
February 6, 2018 Demo Mission n/a Falcon Heavy	n/a	n/a	
February 22, 2018 Paz/Microsat 2a/b 2018-20B,C Falcon 9 v1.2	Communications	499.5 515.5 94.7 97.4	
March 1, 2018 GOES S 2018-022A Atlas 5-541	Earth Science/Meteorology	35,795 35,778 1,436.09 0	
March 6, 2018 Hispasat 30W-6 2018-023A Falcon 9 v1.2	Communications	n/a	
March 30, 2018 Iridium Next 5 2018-30A-H, JK Falcon 9 v1.2	Communications	626 607 97 86.6	
April 2, 2018 Dragon 10.2/CRS-14 2018-032A Falcon 9 v1.2	International Space Station	ISS	Cargo resupply.
April 14, 2018 AFSPC 11 2018-36A,B, E, F Atlas 5-551	Communications	35,651.50 35,647.50 1,431.40 0	Air Force's Continuous Broadcast Augmenting SATCOM. Pathfinder for future missions, demonstrating a maneuverable satellite design.
April 18, 2018 TESS 2018-038A Falcon 9 v1.2	Earth Science	268,488 258 8,758 29.6	
May 5, 2018 InSight 2018-042A Atlas 5-401	Mars Mission	n/a	
May 11, 2018 Bangabandhu 1 Falcon 9 v1.2	Communications	35,793 35,778 1,436.06 0	
May 20, 2018 Cygnus OA-9 2018-046A Antares 230	International Space Station	ISS	Cargo resupply.

Appendix B (cont.)

SUCCESSFUL LAUNCHES TO ORBIT ON U.S. VEHICLES

October 1, 2017–September 30, 2018

Launch Date Spacecraft Name COSPAR* Designation Launch Vehicle	Mission Objectives	Apogee and Perigee (km), Period (min), Inclination to Equator (°)	Remarks
May 22, 2018 Iridium 6/GRACE-FO 2018-047A-B Falcon 9 v1.2	Earth Science	654.14 488.43 96.28 87.3	
June 4, 2018 SES 12 Falcon 9 v1.2	Communications	35,785 35,785 1,436 0	Carries plasma thrusters mounted to articulating robotic arms for nearly all its in-orbit maneuvers, eliminating the need for large conventional liquid-propellant tanks.
June 29, 2018 Dragon 11.2/CRS 15 2018-055B Falcon 9 v1.2	International Space Station	ISS	Cargo resupply.
July 22, 2018 Telstar 19V Falcon 9 v1.2	Communications	35,792 35,780 1,436.1 0.05	Mix of Ka- and Ku-band capacity. Will serve the far north of Canada as well as other regions.
July 25, 2018 Iridium Next 7 2018-061A-H,JK Falcon 9 v1.2	Communications	608 622.8 97 86.6	
August 7, 2018 Merah Putih Falcon 9 v1.2	Communications	35,797 35,789 1,436.10 0	
August 12, 2018 Parker Solar Probe 2018-065A Delta 4H/Star	Science	n/a	
September 10, 2018 Telstar 18V Falcon 9 v1.2	Communications	35,795 35,777 1,436.09 0.04	APT Satellite will use 57.5 percent of capacity.
September 15, 2018 ICESat 2 2018-070A Delta 2-7420	Laser Imaging	468 455 93.8 93.02	Will measure depth of ice with lasers from space.

Appendix C
HUMAN SPACEFLIGHTS

October 1, 2017–September 30, 2018

Spacecraft	Launch Date	Crew	Flight Time (d:h:min)	Highlights
Soyuz MS-07 Expedition 54	December 17, 2017	Anton Shkaplerov Scott D. Tingle Norishige Kanai	168:05:18	Replaced EVA Socket. Finished removal and replacement of Latching End Effector on POA. Progress MS-8 docked to the ISS on February 15, 2018. Installed Ground Strap on Canadarm2.
Soyuz MS-08 Expedition 55	March 21, 2018	A.J. "Drew" Feustel Ricky Arnold Oleg Artemyev	196:18:01	Installed two Wi-Fi antennas on the Node 3 module in preparation for the arrival of ECOSTRESS. Replaced camera and lights used to film NASA TV. SpaceX CRS-14 docked to the ISS on April 4, 2019. Cygnus CRS OA-9E docked on May 24, 2018.
Soyuz MS-09 Expedition 56	June 6, 2018	Serena M. Auñón-Chancellor Alexander Gerst Sergei Prokopyev	196:17:50	Andrew Feustel achieved the third-place ranking for total cumulative time spent spacewalking, with a total of 61 hours and 48 minutes. SpaceX CRS-15 docked with the ISS on July 2, 2018, carrying ECOSTRESS. Manually deployed 4 CubeSats. Installed Icarus Experiment. Progress MS-09 docked with the ISS on July 10, 2018. Kounotori 7 docked with the ISS on September 27, 2018.

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
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

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
SPACE ACTIVITIES OF THE U.S. GOVERNMENT

HISTORICAL TABLE OF BUDGET AUTHORITY

(in millions of inflation-adjusted FY 2018 dollars)

FY	Inflation Factors	NASA Total	NASA Space	DOD[a]	Other[b]	DOE[c]	DOC	DOI	USDA	NSF[d]	DOT	Total Space
1959	6.591	2,182	1,720	3,230	224	224						5,174
1960	6.500	3,406	3,003	3,646	279	279						6,929
1961	6.415	6,184	5,940	5,222	436	436						11,598
1962	6.351	11,590	11,412	8,243	1,264	940	324					20,919
1963	6.277	23,054	22,759	9,729	1,613	1,343	270					34,102
1964	6.197	31,607	31,087	9,910	1,320	1,301	19					42,316
1965	6.093	31,986	31,304	9,590	1,468	1,395	73					42,362
1966	5.965	30,867	30,211	10,074	1,276	1,115	161					41,562
1967	5.789	28,747	27,960	9,632	1,233	1,065	168					38,825
1968	5.594	25,659	24,780	10,751	974	811	157	1	6			36,506
1969	5.350	21,351	20,447	10,769	912	631	107	1	5	167		32,128
1970	5.078	19,022	18,012	8,521	716	523	41	5	5	142		27,249
1971	4.833	16,001	14,986	7,307	783	459	130	10	5	179		23,075
1972	4.614	15,257	14,169	6,491	615	254	143	28	9	182		21,275
1973	4.421	15,058	13,674	7,175	651	239	177	44	9	183		21,501
1974	4.127	12,533	11,386	7,288	652	173	248	37	12	182		19,327
1975	3.741	12,079	10,904	7,078	590	112	239	30	7	201		18,572
1976	3.497	12,415	11,279	6,935	589	80	252	35	14	207		18,802
TQ*	3.395	3,164	2,882	1,562	146	17	75	10	3	41		4,590
1977	3.262	12,453	11,220	7,867	631	72	297	33	20	210		19,718
1978	3.056	12,406	11,071	8,367	691	104	315	31	24	217		20,128
1979	2.828	12,996	11,395	8,585	701	167	277	28	23	206		20,681
1980	2.601	13,628	12,172	10,008	601	104	242	31	36	187		22,781
1981	2.368	13,067	11,821	11,433	555	97	206	28	38	185		23,809
1982	2.214	13,382	12,240	14,788	692	135	321	27	33	177		27,720
1983	2.121	14,585	13,424	19,133	694	83	378	11	42	180		33,252
1984	2.048	15,275	14,046	20,881	809	70	483	6	39	210		35,736
1985	1.982	15,010	13,725	25,306	1,157	67	838	4	30	217		40,189
1986	1.939	15,135	13,890	27,385	924	68	599	4	45	209		42,199
1987	1.896	20,710	18,598	30,881	883	91	527	15	36	212	2	50,362
1988	1.837	16,644	15,285	32,471	1,361	443	647	26	33	211	2	49,117
1989	1.765	19,363	17,823	31,608	989	171	531	30	37	214	5	50,420
1990	1.703	20,986	19,515	26,592	861	135	414	53	43	211	7	46,967
1991	1.644	23,045	21,451	23,317	1,270	413	413	48	43	347	7	46,037
1992	1.604	22,967	21,173	24,099	1,280	358	525	55	47	290	6	46,552
1993	1.567	22,429	20,476	22,109	1,146	259	508	52	39	282	6	43,731
1994	1.534	22,350	19,975	20,196	970	114	479	48	48	275	8	41,141
1995	1.502	20,808	18,839	15,987	1,140	90	529	47	48	417	9	35,965
1996	1.474	20,469	18,530	16,975	1,220	68	696	53	55	340	9	36,725
1997	1.449	19,858	18,045	16,987	1,144	51	649	61	56	318	9	36,175
1998	1.431	19,526	17,628	17,682	1,201	147	622	62	56	305	9	36,511
1999	1.413	19,285	17,599	18,650	1,387	148	812	83	52	283	8	37,636
2000	1.384	18,825	17,330	17,912	1,461	227	796	83	61	286	8	36,703
2001	1.352	19,242	17,990	19,372	1,436	196	780	81	49	314	16	38,797
2002	1.331	19,787	18,460	20,948	1,570	221	857	85	37	354	16	40,979
2003	1.307	20,081	18,769	25,341	1,706	250	848	97	55	440	16	45,815
2004	1.276	19,630	18,281	24,399	1,869	267	951	91	78	467	15	44,548
2005	1.239	20,064	18,869	24,389	1,921	284	1,000	87	90	446	15	45,179
2006	1.200	19,951	18,922	26,542	1,977	294	1,032	98	101	437	14	47,440
2007	1.168	19,027	18,190	26,193	1,963	234	1,066	102	76	472	14	46,346
2008	1.145	19,594	18,890	28,384	1,944	223	987	103	68	548	15	49,218
2009	1.132	20,115	19,549	30,021	2,114	226	1,220	72	30	549	16	51,684
2010	1.122	21,010	20,452	29,692	2,308	228	1,415	75	30	543	17	52,451
2011	1.100	20,276	19,689	29,959	2,404	252	1,588	73	21	453	17	52,052
2012	1.080	19,188	18,572	28,800	2,785	215	2,025	82	7	438	17	50,158
2013	1.060	18,440	17,878	10,818	2,733	196	1,977	89	21	434	16	32,080
2014	1.040	18,352	17,081	10,400	2,839	174	2,087	82	19	461	16	31,532
2015	1.028	18,505	17,359	10,325	3,010	182	2,223	83	19	485	18	30,694
2016	1.018	19,634	18,645	6,967	3,159	178	2,346	87	19	508	22	28,771
2017	1.018	20,009	18,993	10,316	2,995	172	2,214	85	20	480	24	32,305
2018	1.000	20,736	19,976	7,861	2,953	175	2,099	79	16	556	29	30,790

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-2

FEDERAL SPACE ACTIVITIES BUDGET

(in millions of dollars by fiscal year)

	Budget Authority				Budget Outlays			
Federal Agencies	**2016 actual**	**2017 actual**	**2018 actual**	**2019 est.**	**2016 actual**	**2017 actual**	**2018 actual**	**2019 est.**
NASA[1]	18,645	18,993.30	19,976.1	20,775.0	18,225	18,074	19,109.0	20,113
DOD[2, 3]	9,655	10,136	7,861		10,300	10,400	9,296	
DOE[4, 5]	178	172	175.39	187.82	180	173	165.4	167.82
DOC[6]	2,346	2,214	2,099.269	1,698.545	2,053	1,938	2,068.22	1,698.48
DOI	71.2	85.4	78.5		71.1	85	78.5	
USDA[7]	18.5	20.1	15.96	16.17	17.1	18.4	16.08	9.21
DOT	21.8	24.2	28.959	36.449	21.8	24.2	28.959	36.449
NSF[8]	507.5	480.1	555.59	526.29	382.6	352.7	462.15	400.08

1. The FY 2019 estimate is based on the prior year's Outlays versus Budget Authority. FY 2019 Enacted Funding Levels were not available at the time this report was requested. The FY 2019 Budget Authority Estimate is based on the 2019 President's Budget Request.
2. Does not include DOD or Office of the Director of National Intelligence (ODNI) intelligence programs. DOD FY 2016, FY 2017, and FY 2018 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. At the time of preparing this report, the USDA submitted FY 2018 estimates, not actuals.
8. "Actual" = actual obligations.

Appendix D-3

Federal Aeronautics Activities Budget

(in millions of dollars by fiscal year)

	Budget Authority				Budget Outlays			
Federal Agencies	**2016 actual**	**2017 actual**	**2018 actual**	**2019 est.**	**2016 actual**	**2017 actual**	**2018 actual**	**2019 est.**
NASA[1]	640	660	760.0	725.0	609	629	650.0	703
USDA[2, 3]	37.3	38.6	42.21	41.71	36.6	70.7	47.34	25.07
DOD[4, 5]	50,550	53,440	51,466		33,351	33,213	55,208	
DOI	30.4	35	37.7		29.5	35.1	37.5	
DOT	3,004.90	3,014.9	3,420.91	3,173.09	2,733.90	2,674.90	2,696.659	2,956.3

1. The FY 2019 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 2016, FY 2017, and FY 2018 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.

Appendix E-1

Space Policy Directive-2 of May 24, 2018

Streamlining Regulations on Commercial Use of Space

Section 1. Policy. It is the policy of the executive branch to be prudent and responsible when spending taxpayer funds, and to recognize how government actions, including Federal regulations, affect private resources. It is therefore important that regulations adopted and enforced by the executive branch promote economic growth; minimize uncertainty for taxpayers, investors, and private industry; protect national security, public-safety, and foreign policy interests; and encourage American leadership in space commerce.

Sec. 2. Launch and Re-entry Licensing. (a) No later than February 1, 2019, the Secretary of Transportation shall review regulations adopted by the Department of Transportation that provide for and govern licensing of commercial space flight launch and re-entry for consistency with the policy set forth in section 1 of this memorandum and shall rescind or revise those regulations, or publish for notice and comment proposed rules rescinding or revising those regulations, as appropriate and consistent with applicable law.

(b) Consistent with the policy set forth in section 1 of this memorandum, the Secretary of Transportation shall consider the following:

(i) requiring a single license for all types of commercial space flight launch and re-entry operations; and

(ii) replacing prescriptive requirements in the commercial space flight launch and re-entry licensing process with performance-based criteria.

(c) In carrying out the review required by subsection (a) of this section, the Secretary of Transportation shall coordinate with the members of the National Space Council.

(d) The Secretary of Defense, the Secretary of Transportation, and the Administrator of the National Aeronautics and Space Administration shall coordinate to examine all existing U.S. Government requirements, standards, and policies associated with commercial space flight launch and re entry operations from Federal launch ranges and, as appropriate and consistent with applicable law, to minimize those requirements, except those necessary to protect public safety and national security, that would conflict with the efforts of the Secretary of Transportation in implementing the Secretary's responsibilities under this section.

Sec. 3. Commercial Remote Sensing. (a) Within 90 days of the date of this memorandum, the Secretary of Commerce shall review the regulations adopted by the Department of Commerce under Title II of the Land Remote Sensing Policy Act of 1992 (51 U.S.C. 60101 et seq.) for consistency with the policy set forth in section 1 of this memorandum and shall rescind or revise those regulations, or publish for notice and comment proposed rules rescinding or revising those regulations, as appropriate and consistent with applicable law.

(b) In carrying out the review required by subsection (a) of this section, the Secretary of Commerce shall coordinate with the Secretary of State, the Secretary of Defense, the Administrator of the National Aeronautics and Space Administration, and, as appropriate, the Chairman of the Federal Communications Commission.

(c) Within 120 days of the date of the completion of the review required by subsection (a) of this section, the Secretary of Commerce, in coordination with the Secretary of State and the Secretary of Defense, shall transmit to the Director of the Office of Management and Budget a legislative proposal to encourage expansion of the licensing of commercial remote sensing activities. That proposal shall be consistent with the policy set forth in section 1 of this memorandum.

Sec. 4. Reorganization of the Department of Commerce. (a) To the extent permitted by law, the Secretary of Commerce shall consolidate in the Office of the Secretary of Commerce the responsibilities of the Department of Commerce with respect to the Department's regulation of commercial space flight activities.

(b) Within 30 days of the date of this memorandum, the Secretary of Commerce shall transmit to the Director of the Office of Management and Budget a legislative proposal to create within the Department of Commerce an entity with primary responsibility for administering the Department's regulation of commercial space flight activities.

Sec. 5. Radio Frequency Spectrum. (a) The Secretary of Commerce, in coordination with the Director of the Office of Science and Technology Policy, shall work with the Federal Communications Commission to ensure that Federal Government activities related to radio frequency spectrum are, to the extent permitted by law, consistent with the policy set forth in section 1 of this memorandum.

(b) Within 120 days of the date of this memorandum, the Secretary of Commerce and the Director of the Office of Science and Technology Policy, in consultation with the Chairman of the Federal Communications Commission, and in coordination with the members of the National Space Council, shall provide to the President, through the Executive Secretary of the National Space Council, a report on improving the global competitiveness of the United States space sector through radio frequency spectrum policies, regulation, and United States activities at the International Telecommunication Union and other multilateral forums.

Sec. 6. Review of Export Licensing Regulations. The Executive Secretary of the National Space Council, in coordination with the members of the National Space Council, shall:

(a) initiate a review of export licensing regulations affecting commercial space flight activity;

(b) develop recommendations to revise such regulations consistent with the policy set forth in section 1 of this memorandum and with applicable law; and

(c) submit such recommendations to the President, through the Vice President, no later than 180 days from the date of this memorandum.

Sec. 7. 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 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 Transportation is authorized and directed to publish this memorandum in the Federal Register.

Donald J. Trump

The White House,

May 24, 2018

Appendix E-2

Space Policy Directive-3 of June 18, 2018

National Space Traffic Management Policy

Section 1. Policy. For decades, the United States has effectively reaped the benefits of operating in space to enhance our national security, civil, and commercial sectors. Our society now depends on space technologies and space-based capabilities for communications, navigation, weather forecasting, and much more. Given the significance of space activities, the United States considers the continued unfettered access to and freedom to operate in space of vital interest to advance the security, economic prosperity, and scientific knowledge of the Nation.

Today, space is becoming increasingly congested and contested, and that trend presents challenges for the safety, stability, and sustainability of U.S. space operations. Already, the Department of Defense (DoD) tracks over 20,000 objects in space, and that number will increase dramatically as new, more capable sensors come online and are able to detect smaller objects. DoD publishes a catalog of space objects and makes notifications of potential conjunctions (that is, two or more objects coming together at the same or nearly the same point in time and space). As the number of space objects increases, however, this limited traffic management activity and architecture will become inadequate. At the same time, the contested nature of space is increasing the demand for DoD focus on protecting and defending U.S. space assets and interests.

The future space operating environment will also be shaped by a significant increase in the volume and diversity of commercial activity in space. Emerging commercial ventures such as satellite servicing, debris removal, in-space manufacturing, and tourism, as well as new technologies enabling small satellites and very large constellations of satellites, are increasingly outpacing efforts to develop and implement government policies and processes to address these new activities.

To maintain U.S. leadership in space, we must develop a new approach to space traffic management (STM) that addresses current and future operational risks. This new approach must set priorities for space situational awareness (SSA) and STM innovation in science and technology (S&T), incorporate national security considerations, encourage growth of the U.S. commercial space sector, establish an updated STM architecture, and promote space safety standards and best practices across the international community.

The United States recognizes that spaceflight safety is a global challenge and will continue to encourage safe and responsible behavior in space while emphasizing the need for international transparency and STM data sharing. Through this national policy for STM and other national space strategies and policies, the United States will enhance safety and ensure continued leadership, preeminence, and freedom of action in space.

Sec. 2. Definitions. For the purposes of this memorandum, the following definitions shall apply:

(a) Space Situational Awareness shall mean the knowledge and characterization of space objects and their operational environment to support safe, stable, and sustainable space activities.

(b) Space Traffic Management shall mean the planning, coordination, and on-orbit synchronization of activities to enhance the safety, stability, and sustainability of operations in the space environment.

(c) Orbital debris, or space debris, shall mean any human-made space object orbiting Earth that no longer serves any useful purpose.

Sec. 3. Principles. The United States recognizes, and encourages other nations to recognize, the following principles:

(a) Safety, stability, and operational sustainability are foundational to space activities, including commercial, civil, and national security activities. It is a shared interest and responsibility of all spacefaring nations to create the conditions for a safe, stable, and operationally sustainable space environment.

(b) Timely and actionable SSA data and STM services are essential to space activities. Consistent with national security constraints, basic U.S. Government-derived SSA data and basic STM services should be available free of direct user fees.

(c) Orbital debris presents a growing threat to space operations. Debris mitigation guidelines, standards, and policies should be revised periodically, enforced domestically, and adopted internationally to mitigate the operational effects of orbital debris.

(d) A STM framework consisting of best practices, technical guidelines, safety standards, behavioral norms, pre-launch risk assessments, and on-orbit collision avoidance services is essential to preserve the space operational environment.

Sec. 4. Goals. Consistent with the principles listed in section 3 of this memorandum, the United States should continue to lead the world in creating the conditions for a safe, stable, and operationally sustainable space environment. Toward this end, executive departments and agencies (agencies) shall pursue the following goals as required in section 6 of this memorandum:

(a) Advance SSA and STM Science and Technology. The United States should continue to engage in and enable S&T research and development to support the practical applications of SSA and STM. These activities include improving fundamental knowledge of the space environment, such as the characterization of small debris, advancing the S&T of critical SSA inputs such as observational data, algorithms, and models necessary to improve SSA capabilities, and developing new hardware and software to support data processing and observations.

(b) Mitigate the effect of orbital debris on space activities. The volume and location of orbital debris are growing threats to space activities. It is in the interest of all to minimize new debris and mitigate effects of existing debris. This fact, along with increasing numbers of active satellites, highlights the need to update existing orbital debris mitigation guidelines and practices to enable more efficient and effective compliance, and establish standards that can be adopted internationally. These trends also highlight the need to establish satellite safety design guidelines and best practices.

(c) Encourage and facilitate U.S. commercial leadership in S&T, SSA, and STM. Fostering continued growth and innovation in the U.S. commercial space sector, which includes S&T, SSA, and STM activities, is in the national interest of the United States. To achieve this goal, the U.S. Government should streamline processes and reduce regulatory burdens that could inhibit commercial sector growth and innovation, enabling the U.S. commercial sector to continue to lead the world in STM-related technologies, goods, data, and services on the international market.

(d) Provide U.S. Government-supported basic SSA data and basic STM services to the public. The United States should continue to make available basic SSA data and basic STM services (including conjunction and reentry notifications) free of direct user fees while supporting new opportunities for U.S. commercial and non-profit SSA data and STM services.

(e) Improve SSA data interoperability and enable greater SSA data sharing. SSA data must be timely and accurate. It is in the national interest of the United States to improve SSA data interoperability and enable greater SSA data sharing among all space operators, consistent with national security constraints. The United States should seek to lead the world in the development of improved SSA data standards and information sharing.

(f) Develop STM standards and best practices. As the leader in space, the United States supports the development of operational standards and best practices to promote safe and responsible behavior in space. A critical first step in carrying out that goal is to develop U.S.-led minimum safety standards and best practices to coordinate space traffic. U.S. regulatory agencies should, as appropriate, adopt these standards and best practices in domestic regulatory frameworks and use them to inform and help shape international consensus practices and standards.

(g) Prevent unintentional radio frequency (RF) interference. Growing orbital congestion is increasing the risk to U.S. space assets from unintentional RF interference. The United States should continue to improve policies, processes, and technologies for spectrum use (including allocations and licensing) to address these challenges and ensure appropriate spectrum use for current and future operations.

(h) Improve the U.S. domestic space object registry. Transparency and data sharing are essential to safe, stable, and sustainable space operations. Consistent with national security constraints, the United States should streamline the interagency process to ensure accurate and timely registration submissions to the United Nations (UN), in accordance with our international obligations under the Convention on Registration of Objects Launched into Outer Space.

(i) Develop policies and regulations for future U.S. orbital operations. Increasing congestion in key orbits and maneuver-based missions such as servicing, survey, and assembly will drive the need for policy development for national security, civil, and commercial sector space activities. Consistent with U.S. law and international obligations, the United States should regularly assess existing guidelines for non-government orbital activities, and maintain a timely and responsive regulatory environment for licensing these activities.

Sec. 5. Guidelines. In pursuit of the principles and goals of this policy, agencies should observe the following guidelines:

(a) Managing the Integrity of the Space Operating Environment.

(i) Improving SSA coverage and accuracy. Timely, accurate, and actionable data are essential for effective SSA and STM. The United States should seek to minimize deficiencies in SSA capability, particularly coverage in regions with limited sensor availability and sensitivity in detection of small debris, through SSA data sharing, the purchase of SSA data, or the provision of new sensors.

New U.S. sensors are expected to reveal a substantially greater volume of debris and improve our understanding of space object size distributions in various regions of space. However, very small debris may not be sufficiently tracked to enable or justify actionable collision avoidance decisions. As a result, close conjunctions and even collisions with unknown objects are possible, and satellite operators often lack sufficient insight to assess their level of risk when making maneuvering decisions. The United States should develop better tracking capabilities, and new means to catalog such debris, and establish a quality threshold for actionable collision avoidance warning to minimize false alarms.

Through both Government and commercial sector S&T investment, the United States should advance concepts and capabilities to improve SSA in support of debris mitigation and collision avoidance decisions.

(ii) Establishing an Open Architecture SSA Data Repository. Accurate and timely tracking of objects orbiting Earth is essential to preserving the safety of space activities for all. Consistent with section 2274 of title 10, United States Code, a basic level of SSA data in the form of the publicly releasable portion of the DoD catalog is and should continue to be provided free of direct user fees. As additional sources of space tracking data become available, the United States has the opportunity to incorporate civil, commercial, international, and other available data to allow users to enhance and refine this service. To facilitate greater data sharing with satellite operators and enable the commercial development

of enhanced space safety services, the United States must develop the standards and protocols for creation of an open architecture data repository. The essential features of this repository would include:

- Data integrity measures to ensure data accuracy and availability;
- Data standards to ensure sufficient quality from diverse sources;
- Measures to safeguard proprietary or sensitive data, including national security information;
- The inclusion of satellite owner-operator ephemerides to inform orbital location and planned maneuvers; and
- Standardized formats to enable development of applications to leverage the data.

To facilitate this enhanced data sharing, and in recognition of the need for DoD to focus on maintaining access to and freedom of action in space, a civil agency should, consistent with applicable law, be responsible for the publicly releasable portion of the DoD catalog and for administering an open architecture data repository. The Department of Commerce should be that civil agency.

(iii) Mitigating Orbital Debris. It is in the interest of all space operators to minimize the creation of new orbital debris. Rapid international expansion of space operations and greater diversity of missions have rendered the current U.S. Government Orbital Debris Mitigation Standard Practices (ODMSP) inadequate to control the growth of orbital debris. These standard practices should be updated to address current and future space operating environments.

The United States should develop a new protocol of standard practices to set broader expectations of safe space operations in the 21st century. This protocol should begin with updated ODMSP, but also incorporate sections to address operating practices for large constellations, rendezvous and proximity operations, small satellites, and other classes of space operations. These overarching practices will provide an avenue to promote efficient and effective space safety practices with U.S. industry and internationally.

The United States should pursue active debris removal as a necessary long-term approach to ensure the safety of flight operations in key orbital regimes. This effort should not detract from continuing to advance international protocols for debris mitigation associated with current programs.

(b) Operating in a Congested Space Environment.

(i) Minimum Safety Standards and Best Practices. The creation of minimum standards for safe operation and debris mitigation derived in part from the U.S. Government ODMSP, but incorporating other standards and best practices, will best ensure the safe operation of U.S. space activities. These safety guidelines should consider maneuverability, tracking, reliability, and disposal.

The United States should eventually incorporate appropriate standards and best practices into Federal law and regulation through appropriate rulemaking or licensing actions. These guidelines should encompass protocols for all stages of satellite operation from design through end-of-life.

Satellite and constellation owners should participate in a pre-launch certification process that should, at a minimum, consider the following factors:

- Coordination of orbit utilization to prevent conjunctions;
- Constellation owner-operators' management of self-conjunctions;
- Owner-operator notification of planned maneuvers and sharing of satellite orbital location data;
- On-orbit tracking aids, including beacons or sensing enhancements, if such systems are needed;

- Encryption of satellite command and control links and data protection measures for ground site operations;
- Appropriate minimum reliability based on type of mission and phase of operations;
- Effect on the national security or foreign policy interests of the United States, or international obligations; and
- Self-disposal upon the conclusion of operational lifetime, or owner-operator provision for disposal using active debris removal methods.

(ii) On-Orbit Collision Avoidance Support Service. Timely warning of potential collisions is essential to preserving the safety of space activities for all. Basic collision avoidance information services are and should continue to be provided free of direct user fees. The imminent activation of more sensitive tracking sensors is expected to reveal a significantly greater population of the existing orbital debris background as well as provide an improved ability to track currently catalogued objects. Current and future satellites, including large constellations of satellites, will operate in a debris environment much denser than presently tracked. Preventing on-orbit collisions in this environment requires an information service that shares catalog data, predicts close approaches, and provides actionable warnings to satellite operators. The service should provide data to allow operators to assess proposed maneuvers to reduce risk. To provide on-orbit collision avoidance, the United States should:

- Provide services based on a continuously updated catalog of satellite tracking data;
- Utilize automated processes for collision avoidance;
- Provide actionable and timely conjunction assessments; and
- Provide data to operators to enable assessment of maneuver plans.

To ensure safe coordination of space traffic in this future operating environment, and in recognition of the need for DoD to focus on maintaining access to and freedom of action in space, a civil agency should be the focal point for this collision avoidance support service. The Department of Commerce should be that civil agency.

(c) Strategies for Space Traffic Management in a Global Context.

(i) Protocols to Prevent Orbital Conjunctions. As increased satellite operations make lower Earth orbits more congested, the United States should develop a set of standard techniques for mitigating the collision risk of increasingly congested orbits, particularly for large constellations. Appropriate methods, which may include licensing assigned volumes for constellation operation and establishing processes for satellites passing through the volumes, are needed.

The United States should explore strategies that will lead to the establishment of common global best practices, including:

- A common process addressing the volume of space used by a large constellation, particularly in close proximity to an existing constellation;
- A common process by which individual spacecraft may transit volumes used by existing satellites or constellations; and
- A set of best practices for the owner-operators of utilized volumes to minimize the long-term effects of constellation operations on the space environment (including the proper disposal of satellites, reliability standards, and effective collision avoidance).

(ii) Radio Frequency Spectrum and Interference Protection. Space traffic and RF spectrum use have traditionally been independently managed processes. Increased congestion in key orbital regimes creates a need for improved and increasingly dynamic methods to coordinate activities in both the physical and spectral domains, and may introduce new interdependencies. U.S. Government efforts in STM should address the following spectrum management considerations:

- Where appropriate, verify consistency between policy and existing national and international regulations and goals regarding global access to, and operation in, the RF spectrum for space services;
- Investigate the advantages of addressing spectrum in conjunction with the development of STM systems, standards, and best practices;
- Promote flexible spectrum use and investigate emerging technologies for potential use by space systems; and
- Ensure spectrum-dependent STM components, such as inter-satellite safety communications and active debris removal systems, can successfully access the required spectrum necessary to their missions.

(iii) Global Engagement. In its role as a major spacefaring nation, the United States should continue to develop and promote a range of norms of behavior, best practices, and standards for safe operations in space to minimize the space debris environment and promote data sharing and coordination of space activities. It is essential that other spacefaring nations also adopt best practices for the common good of all spacefaring states. The United States should encourage the adoption of new norms of behavior and best practices for space operations by the international community through bilateral and multilateral discussions with other spacefaring nations, and through U.S. participation in various organizations such as the Inter-Agency Space Debris Coordination Committee, International Standards Organization, Consultative Committee for Space Data Systems, and UN Committee on the Peaceful Uses of Outer Space.

Sec. 6. Roles and Responsibilities. In furtherance of the goals described in section 4 and the guidelines described in section 5 of this memorandum, agencies shall carry out the following roles and responsibilities:

(a) Advance SSA and STM S&T. Members of the National Space Council, or their delegees, shall coordinate, prioritize, and advocate for S&T, SSA, and STM, as appropriate, as it relates to their respective missions. They should seek opportunities to engage with the commercial sector and academia in pursuit of this goal.

(b) Mitigate the Effect of Orbital Debris on Space Activities.

(i) The Administrator of the National Aeronautics and Space Administration (NASA Administrator), in coordination with the Secretaries of State, Defense, Commerce, and Transportation, and the Director of National Intelligence, and in consultation with the Chairman of the Federal Communications Commission (FCC), shall lead efforts to update the U.S. Orbital Debris Mitigation Standard Practices and establish new guidelines for satellite design and operation, as appropriate and consistent with applicable law.

(ii) The Secretaries of Commerce and Transportation, in consultation with the Chairman of the FCC, will assess the suitability of incorporating these updated standards and best practices into their respective licensing processes, as appropriate and consistent with applicable law.

(c) Encourage and Facilitate U.S. Commercial Leadership in S&T, SSA, and STM. The Secretary of Commerce, in coordination with the Secretaries of Defense and Transportation, and the NASA Administrator, shall lead efforts to encourage and facilitate continued U.S. commercial leadership in SSA, STM, and related S&T.

(d) Provide U.S. Government-Derived Basic SSA Data and Basic STM Services to the Public.

(i) The Secretaries of Defense and Commerce, in coordination with the Secretaries of State and Transportation, the NASA Administrator, and the Director of National Intelligence, should cooperatively develop a plan for providing basic SSA data and basic STM services either directly or through a partnership with industry or academia, consistent with the guidelines of sections 5(a)(ii) and 5(b)(ii) of this memorandum.

(ii) The Secretary of Defense shall maintain the authoritative catalog of space objects.

(iii) The Secretaries of Defense and Commerce shall assess whether statutory and regulatory changes are necessary to effect the plan developed under subsection (d)(i) of this section, and shall pursue such changes, along with any other needed changes, as appropriate.

(e) Improve SSA Data Interoperability and Enable Greater SSA Data Sharing.

(i) The Secretary of Commerce, in coordination with the Secretaries of State, Defense, and Transportation, the NASA Administrator, and the Director of National Intelligence, shall develop standards and protocols for creation of an open architecture data repository to improve SSA data interoperability and enable greater SSA data sharing.

(ii) The Secretary of Commerce shall develop options, either in-house or through partnerships with industry or academia, assessing both the technical and economic feasibility of establishing such a repository.

(iii) The Secretary of Defense shall ensure that release of data regarding national security activities to any person or entity with access to the repository is consistent with national security interests.

(f) Develop Space Traffic Standards and Best Practices. The Secretaries of Defense, Commerce, and Transportation, in coordination with the Secretary of State, the NASA Administrator, and the Director of National Intelligence, and in consultation with the Chairman of the FCC, shall develop space traffic standards and best practices, including technical guidelines, minimum safety standards, behavioral norms, and orbital conjunction prevention protocols related to pre-launch risk assessment and on-orbit collision avoidance support services.

(g) Prevent Unintentional Radio Frequency Interference. The Secretaries of Commerce and Transportation, in coordination with the Secretaries of State and Defense, the NASA Administrator, and the Director of National Intelligence, and in consultation with the Chairman of the FCC, shall coordinate to mitigate the risk of harmful interference and promptly address any harmful interference that may occur.

(h) Improve the U.S. Domestic Space Object Registry. The Secretary of State, in coordination with the Secretaries of Defense, Commerce, and Transportation, the NASA Administrator, and the Director of National Intelligence, and in consultation with the Chairman of the FCC, shall lead U.S. Government efforts on international engagement related to international transparency and space object registry on SSA and STM issues.

(i) Develop Policies and Regulations for Future U.S. Orbital Operations. The Secretaries of Defense, Commerce, and Transportation, in coordination with the Secretary of State, the NASA Administrator,

and the Director of National Intelligence, shall regularly evaluate emerging trends in space missions to recommend revisions, as appropriate and necessary, to existing SSA and STM policies and regulations.

Sec. 7. 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 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 Commerce is authorized and directed to publish this memorandum in the Federal Register.

Donald J. Trump

The White House,

June 18, 2018

Acronyms

3DEP	3D Elevation Program

A

AARGM	Advanced Anti-Radiation Guided Missile
ABoVE	Arctic-Boreal Vulnerability Experiment
ACARE	Advisory Council for Aviation Research and innovation in Europe
ACE	Advanced Composition Explorer
ACEP	Agricultural Conservation Easement Program
ACES	Atomic Clock Ensemble in Space
ACE-T-6	Advanced Colloids Experiment-Temperature-6
ACT	Atacama Cosmology Telescope
ADEPT	Adaptable, Deployable Entry and Placement Technology
ADS-B	Automatic Dependent Surveillance–Broadcast
AE	Archive Explorer
AEDC	Arnold Engineering Development Center
AEFS	Advanced Electronic Flight Strips
AEHF	Advanced Extremely High Frequency
AES	Advanced Exploration Systems
AFB	Air Force Base
AFRCO	Air Force Rapid Capabilities Office
AFRL	Air Force Research Laboratory
AFSPC	Air Force Space Command
AFSS	Autonomous Flight Safety System
AGS	Atmospheric and Geospace Science Division
AIA	Atmospheric Imaging Assembly
AIS	Automatic Identification System
AIT	American Institute in Taiwan
ALMA	Atacama Large Millimeter/Submillimeter Array
ALPACA	Advanced Cryogenic L-band Phased Array Camera for Arecibo
AM	additive manufacturing
AMC	Additive Manufacturing Consortium
AMISR	Advanced Modular Incoherent-Scatter Radar
AMPERE	Active Magnetosphere and Planetary Electrodynamics Response Experiment
AMS	Autonomous Modular Sensor; Alpha Magnetic Spectrometer
AMSR	Advanced Microwave Scanning Radiometer
ANSI	American National Standards Institute
AO	Arecibo Observatory
AoR	Area of Responsibility
APD	Astrophysics Division
APKWS	Advanced Precision Kill Weapon System
APL	Applied Physics Laboratory
AR	Aerojet Rocketdyne Holdings, Inc.
ARD	Analysis Ready Data
ARM	Atmospheric Radiation Measurement Research Facility
ARMD	Aeronautics Research Mission Directorate
ARPA-E	Advanced Research Projects Agency–Energy
ARS	Agricultural Research Service
AS	Atmosphere Section

ASB	Agricultural Statistics Board
ASBU	Aviation System Block Upgrade
ASD	agricultural statistics district
ASME	American Society of Mechanical Engineers
AST	Office of Commercial Space Transportation (FAA); Division of Astronomical Sciences (NSF)
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
ATDS	Advanced Threat Detection System
ATHENA	Advanced Telescope for High-ENergy Astrophysics
ATLAS	Advanced Twin Lifting and Aerobic System
ATM	air traffic management
ATom	Atmospheric Tomography
AVC	Arms Control, Verification and Compliance
AWiFS	Advanced Wide Field Sensor

B

BAA	Broad Agency Announcement
BABAR	Broadband Absolute Bolometer Array
BAER	Burned Area Emergency Response
BEAM	Bigelow Expandable Activity Module
BECCAL	Bose-Einstein Condensate Cold Atom Laboratory
BICEP	Background Imaging of Cosmic Extragalactic Polarization
BICM	Barrier Island Comprehensive Monitoring
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
BMC2	Battle Management Command and Control
BMG	Bulk Metallic Glass
BNL	Brookhaven National Laboratory
BOEM	Bureau of Ocean Energy Management
BOR	Bureau of Reclamation
BPA	Brine Processor Assembly
BPS	Biological and Physical Sciences

C

C&N	communication and navigation
C2	command and control
C2V2	Common Communications for Visiting Vehicles
C4I	Command, Control, Communications, Computers, and Intelligence
CAE	Center for Agribusiness Excellence
CAESR	Carbon Absolute Electrical Substitution Radiometer
CAL	Cold Atom Laboratory
CAS	Convergent Aeronautics Solutions
CASIS	Center for the Advancement of Science in Space
CCAFS	Cape Canaveral Air Force Station
CCC	Commodity Credit Corporation
CCOR	compact coronagraph
CCS	Counter Communications System
CCSC	Collaborations for Commercial Space Capabilities

CCSDS	Consultative Committee for Space Data Systems
CDL	Cropland Data Layer
CDR	Critical Design Review
CEC	Commission for Environmental Cooperation
CEDAR	Coupling, Energetics, and Dynamics of Atmospheric Regions
CENTCOM	Central Command
CEO	chief executive officer
CEPS	Center for Earth and Planetary Studies
CERES FM6	Clouds and the Earth's Radiant Energy System Flight Model 6
CERP	Comprehensive Everglades Restoration Plan
CfA	Center for Astrophysics | Harvard & Smithsonian
CFC	chlorofluorocarbon
CFD	computational fluid dynamics
CFO	Carlsbad Field Office
CHARA	Center for High Angular Resolution Astronomy
CHIRPS	Climate Hazards Group Infrared Precipitation with Stations
CHNS	Committee for Homeland and National Security
CIR	Color Infrared
CIRAS	Commercial Infrastructure for Robotic Assembly and Services
CLaRe	Climate Landscape Response
CLASS	Cosmic Large Angular Scale Survey
CLPS	Commercial Lunar Payload Services
CM	Crew Module
CMB	cosmic microwave background
CMDA	Civil Maritime Domain Awareness
CME	Coronal Mass Ejection
CMS	CSpOC Mission System
CMWS	Common Missile Warning System
CNES	Centre National d'Études Spatiales
CNT	carbon nanotube
CNT ESR	Carbon Nano-tube Electrical Substitution Radiometer
CO	carbon monoxide
COA	Course of Action
CONOPS	Concept of Operations
CONUS	contiguous United States
COPUOS	UN Committee on the Peaceful Uses of Outer Space
COSMIC	Constellation Observing System for Meteorology, Ionosphere, and Climate
COSPAS-SARSAT	Search and Rescue Satellite-Aided Tracking
COWVR	Compact Ocean Wind Vector Radiometer
CPRA	Coastal Protection and Restoration Authority
CrIS	Cross-track Infrared Sounder
CRP	constant-rate production
CRS	Commercial Resupply Services
CRSRA	Commercial Remote Sensing Regulatory Affairs
CS	Commercial Service
CSIM	Compact Solar Irradiance Monitor
CSLI	CubeSat Launch Initiative
CSP	Cold Spray Process
CSpOC	Combined Space Operations Center
CUBES	Center for Utilization of Biological Engineering in Space
CVN	aircraft carrier with nuclear propulsion
CVW	Carrier Air Wing
CWDP	Commercial Weather Data Pilot
CYGNSS	Cyclone Global Navigation Satellite System

D

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
DEM	digital elevation model
DG-GROW	Directorate General for Internal Market, Industry, Entrepreneurship and Small Medium Enterprise
DKIST	Daniel K. Inouye Solar Telescope
DLC	Descent and Landing Computer
DLR	German Aerospace Center
DMC	Disaster Monitoring Constellation
DMSP	Defense Meteorological Satellite Program
dNBR	Delta NBR
dNDVI	difference between leaf-on and leaf-off NDVI values
DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
DOI	Department of the Interior
DopplerScatt	Doppler Scatterometer
DOS	Department of State
DOT	Department of Transportation
DSA	Deep Synoptic Array
DSAC	Deep Space Atomic Clock
DSCOVR	Deep Space Climate Observatory
DSN	Deep Space Network
DSP	Defense Support Program
DSWE	Dynamic Surface Water Extent
DTN	Disruption Tolerant Networking

E

EA	Environmental Assessment
EAGLE	ESPA Augmented Geosynchronous Laboratory Experiment
EBIS	Electron Beam Ion Source
EC	European Commission
ECAMS	Environmental Continuous Air Monitors
ECMWF	European Centre for Medium-Range Weather Forecasts
ECOSTRESS	ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station
eCryo	Evolvable Cryogenics
EDU	Engineering Development Unit
EEAS	European External Action Service
EELV	Evolved Expendable Launch Vehicle
EGS	Exploration Ground Systems
EHT	Event Horizon Telescope
EIS	Environmental Impact Statement
ELV	expendable launch vehicle
EM-1	Exploration Mission–1
EM-2	Exploration Mission–2
EO	Earth observation
EOS	Earth Observing System
EPS	Enhanced Polar System
ERG	Exploration of energization and Radiation in Geospace
EROS	Earth Resources Observation and Science

ESA	European Space Agency
ESBMC2	Enterprise Space Battle Management Command and Control
ESD	Exploration Systems Development; Earth Science Division
ESIM	earth station in motion
ESP	Efficient Space Procurement; Environmental Studies Program
ESPA	EELV Secondary Payload Adapter
ESR	Emergency Stabilization and Rehabilitation
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
EVWHS	Enhanced View Web Hosting Service
EWS	Electro-optical/infrared Weather System
EWS-G	EWS-Geostationary
EXIM	Export-Import Bank
EXIS	EUV and X-ray Irradiance Sensor
EXPORTS	Export Processes in the Ocean from Remote Sensing

F

FAA	Federal Aviation Administration
FabLab	Fabrication Laboratory
FAB-T	Family of Advanced Beyond-Line-of-Sight Terminals
FACA	Federal Advisory Committee Act
FAS	Foreign Agricultural Service
FAS/OGA	Foreign Agricultural Service Office of Global Analysis
FCC	Federal Communications Commission
FCIC	Federal Crop Insurance Corporation
FDEM	frequency-domain electromagnetic
FDSS	Faculty Development in Space Sciences
FES	Office of Fusion Energy Sciences
FEWS NET	Famine Early Warning Systems Network
FGST	Fermi Gamma-ray Space Telescope
FIA	Forest Inventory and Analysis
FOC	Full Operational Capability
FOD	foreign object debris
FOR	Flight Operations Review
FOXSI	Focusing Optics X-ray Solar Imager
FRB	Fast Radio Burst
FSA	Farm Service Agency
FVL	Future Vertical Lift
FWS	Fish and Wildlife Service
FY	fiscal year

G

GBD	Global Burst Detector
GBMASH	Ground Based Manufacturing and Assembly System Hardware
Gbps	gigabits per second
GCD	Game Changing Development
GCOM-W	Global Change Observation Mission–Water

GCR	Galactic Cosmic Ray
GDC	Geospace Dynamics Constellation
GEE	Google Earth Engine
GEM	Geospace Environment Modeling
GEO	Geosynchronous Earth Orbit; Directorate for Geosciences
GEO-AGS	Directorate for Geosciences' Division of Atmospheric and Geospace Sciences
GeV	gigaelectronvolt
GF	Geospace Facilities
GIS	Geographic Information Systems; graphite impact shell
GLAM	Global Agricultural Monitoring
G-LiHT	Goddard's Lidar, Hyperspectral, and Thermal Imager
GMT	Giant Magellan Telescope
GNC-A	GEONETCast Americas
GNSS	Global Navigation Satellite Systems
GO1	GOLauncher1
GOES	Geostationary Operational Environmental Satellite
GOLD	Global-scale Observations of the Limb and Disk
GONG	Global Oscillations Network Group
GPIM	Green Propellant Infusion Mission
GPM	Global Precipitation Measurement
GPS	Global Positioning System
GPS IIIF	GPS III Follow-on
GPSRO	GPS radio occultation
GPS SAR	GPS Search and Rescue
GRACE	Gravity Recovery and Climate Experiment
GRACE-FO	Gravity Recovery and Climate Experiment Follow-On
GRB	GOES Rebroadcast
GRC	Glenn Research Center
G-REALM	Global Reservoir and Lake Monitor
GS	Geospace Section
GSFC	Goddard Space Flight Center
GSSAP	Geosynchronous Space Situational Awareness Program
GUT	grand-unified theory

H

HARM	High-Speed Anti-Radiation Missile
HEO	Highly Elliptical Orbit
HERA	Human Exploration Research Analog; Hybrid Electronic Radiation Assessor; Hydrogen Epoch of Reionization Array
HEAT	High Elevation Antarctic Terahertz
HF	high-frequency
HFIR	High Flux Isotope Reactor
HIAD	Hypersonic Inflatable Aerodynamic Decelerator
HiRISE	High Resolution Imaging Science Experiment
HPD	Heliophysics Division
HPSC	High Performance Spaceflight Computing
HRP	Human Research Program
HTV	H-II Transfer Vehicle
HWIL	Hardware-in-the-Loop

I

I&W	Indications and Warning
IBEX	Interstellar Boundary Explorer

IC	Intelligence Community
ICAO	International Civil Aviation Organization
ICBM	intercontinental ballistic missile
ICESat	Ice, Cloud, and land Elevation Satellite
ICEX	Ice Exercise
ICG	International Committee on GNSS
ICNO	IceCube Neutrino Observatory
ICON	Ionospheric Connection Explorer
IfSAR	interferometric synthetic aperture radar
IFUSI	Improved Fundamental Understanding of Super Insulation
IMAP	Interstellar Mapping and Acceleration Probe
INL	Idaho National Laboratory
INSCOM	Intelligence and Securities Command
InSight	Interior Exploration using Seismic Investigations, Geodesy and Heat Transport
IOAG	Interagency Operations Advisory Group
IOC	Initial Operational Capability
IOD	Indian Ocean Dipole
IPAD	International Production Assessment Division
IPTE	Improved Performance Technology Engine
IPv6	Internet Protocol version 6
IR	infrared
IRAC	Infrared Array Camera
IRIS	Interface Region Imaging Spectrograph
IRS-2	Indian Resourcesat–2
ISARA	Integrated Solar Array Reflectarray Antenna
ISIL, ISIS	Islamic State
ISM	In-Space Manufacturing
ISPF	In Space Propulsion Facility
ISR	Intelligence, Surveillance, and Reconnaissance
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
IXPE	Imaging X-ray Polarimetry Explorer

J

JAGM	Joint Air-to-Ground Missile
JASD	Joint Agency Satellite Division
JAXA	Japan Aerospace Exploration Agency
JMR-TD	Joint Multi-Role Technology Demonstrator
JPL	Jet Propulsion Laboratory
JPSS	Joint Polar Satellite System
JPSS-1	Joint Polar Satellite System–1
JRC	Joint Research Centre
JSC	Johnson Space Center
JSF	Joint Strike Fighter
JSpOC	Joint Space Operations Center
JUICE	Jupiter Icy Moons Explorer

K

KAPA	Keck All-Sky Precision Adaptive Optics
KARI	Korea Aerospace Research Institute
KRUSTY	Kilopower Reactor Using Stirling Technology
KSC	Kennedy Space Center
K–T boundary	Cretaceous–Tertiary boundary

L

LAANC	Low Altitude Authorization and Notification Capability
LANL	Los Alamos National Laboratory
LASP	Laboratory for Atmospheric and Space Physics
LAT	Large Area Telescope
LCAAT	Low Cost Attritable Aircraft Technologies
LCLS	Linac Coherent Light Source
LCMS	Landscape Change Monitoring System
LCRD	Laser Communication Relay Demonstration
LCUSP	Low-Cost Upper Stage-Class Propulsion
LEE	Latching End Effector
LEO	low-Earth orbit
LERZ	Lower East Rift Zone
LIBS	Laser Induced Breakdown Spectroscopy
lidar	light detection and ranging
LIGO	Laser Interferometer Gravitational-wave Observatory
LISS	Linear Imaging Self Scanning
LLAMAS	Large Lenslet Array Magellan Spectrograph
LLNL	Lawrence Livermore National Laboratory
LOFTID	LEO-based Flight Test of an Inflatable Decelerator
LOLA	Lunar Orbiter Laser Altimeter
LRASM	Long-Range Anti-Ship Missile
LRO	Lunar Reconnaissance Orbiter
LSA	launch service agreement
LSC	Legal Subcommittee
LSP	Launch Services Program
LSST	Large Synoptic Survey Telescope
LST	Land Surface Temperature
LTRS	Launch and Test Range System
LTS	Working Group on Long-Term Sustainability of Outer Space Activities
Lunar CATALYST	Lunar Cargo Transportation and Landing by Soft Touchdown
LunIR	Lunar Infrared
LUSI	LUnar Spectral Irradiance
LWA	Long Wavelength Array

M

M1	primary mirror (DKIST)
M3	Moon Mineralogy Mapper
MAF	Michoud Assembly Facility
MANPADS	Man Portable Air Defense Systems
MAPS	MMT Adaptive optics exoPlanet characterization System
MARCI	Mars Color Imager
MarCO	Mars Cube One
MARSIS	Mars Advanced Radar for Subsurface and Ionosphere Sounding
MAVEN	Mars Atmosphere and Volatile Evolution

Mb/s	megabits per second
MBSE	Model-Based Systems Engineering
MCS	Mars Climate Sounder
MDXR	Missile Defense Transfer Radiometer
MEDA	Mars Environmental Dynamics Analyzer
MEDLI-2	Mars Entry, Descent, and Landing Instrumentation–2
MENA	Middle East North Africa
MEO	medium-Earth orbit
MEOSAR	Medium Earth Orbit Search and Rescue
MEP	Manufacturing Extension Partnership
MER	Mars Exploration Rover
Micro-X	High-Resolution Microcalorimeter X-ray Imaging Rocket
MIDEX	Medium-Class Explorer
MILSATCOM	Military Satellite Communications Systems Directorate
MinXSS	Miniature X-ray Solar Spectrometer
MKID	microwave kinetic-inductance detector
MMS	Magnetospheric Multiscale
MMRTG	Multi-Mission Radioisotope Thermoelectric Generator
MMT	Multiple Mirror Telescope
MOBY	Marine Optical BuoY
MODIS	Moderate Resolution Imaging Spectroradiometer
MoFA	Japan's Ministry of Foreign Affairs
MOPITT	Measurement of Pollution in the Troposphere
MOU	Memorandum of Understanding
MOXIE	Mars Oxygen In-Situ Resource Utilization Experiment
MPS	Mathematics and Physical Sciences
MRLC	Multi-Resolution Land Characteristics Consortium
MRO	Mars Reconnaissance Orbiter
MRR	Mission Readiness Review
MSIP	Mid-Scale Innovations Program
MSL	Mars Science Laboratory
MVP	Multi-use Variable-g Platform

N

N	nitrogen
N_2	dinitrogen
NAAMES	North Atlantic Aerosols and Marine Ecosystems Study
NAAQS	National Ambient Air Quality Standards
NAC	NextGen Advisory Committee
NAICS	North American Industry Classification System
NAIP	National Agriculture Imagery Program
NALCMS	North American Land Change Monitoring System
NANOGrav	North American Nanohertz Observatory for Gravitational Waves
NAS	National Academy of Sciences; Naval Air Station; National Airspace System
NASA	National Aeronautics and Space Administration
NASA-ISRO	NASA–Indian Space Research Organization
NASM	National Air and Space Museum
NASS	National Agricultural Statistics Service
NBR	Normalized Burn Ratio
NCEP	National Centers for Environmental Prediction
NDAA	National Defense Authorization Act
NDOP	National Digital Orthoimagery Program
NDS	NASA Docking System
NDVI	Normalized Difference Vegetation Index

NE	Office of Nuclear Energy
NEK	Nazemnyy Eksperimental'nyy Kompleks
NEN	Near Earth Network
NEO	near-Earth object
NEPA	National Environmental Policy Act
NERSC	National Energy Research Supercomputing Center
NET	No Earlier Than
NextGen	Next Generation Air Transportation System
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
NGSC	Next Generation Strike Capability
NIAC	NASA Innovative Advanced Concepts
NICER	Neutron-star Interior Composition Explorer
NISAR	NASA–Indian Space Research Organization Synthetic Aperture Radar
NIST	National Institute of Standards and Technology
NLCD	National Land Cover Database
NLIP	National Land Imaging Program
NMNH	National Museum of Natural History
NMSO	New Mexico State Office
NNSA	National Nuclear Security Administration
NNSS	Nevada National Security Site
NO_2	nitrogen dioxide
NOAA	National Oceanic and Atmospheric Administration
NOAO	National Optical Astronomy Observatory
NOC	National Operations Center
NO_x	nitrogen oxide
NP	Office of Nuclear Physics
NPN	National Phenology Network
NPP	National Polar Partnership
NPS	National Park Service
NRAO	National Radio Astronomy Observatory
NRCS	Natural Resources Conservation Service
NRI	National Resources Inventory
NROL	National Reconnaissance Office Launch
NS-10	University Nanosat Program, round 10
NSDC	National Space Defense Center
NSF	National Science Foundation
NSPO	National Space Organization
NSO	National Solar Observatory
NSRL	NASA Space Radiation Laboratory
NSS	National Security Space
NSTC	National Science and Technology Council
NSWAP	National Space Weather Action Plan
NSWS	National Space Weather Strategy
NTP	Nuclear Thermal Propulsion
NuSTAR	Nuclear Spectroscopic Telescope Array
NWP	numerical weather prediction

O

OASuW	Offensive Anti-Surface Warfare
OCO-2	Orbiting Carbon Observatory-2

OCONUS	Outside CONUS
OCS	Outer Continental Shelf
OCSD	Optical Communications and Sensor Demonstration
OCSLA	Outer Continental Shelf Lands Act
OCX	Operational Control System
ODNI	Office of the Director of National Intelligence
OECD	Organization for Economic Cooperation and Development
OES/SAT	Oceans, Environment and Science /Office of Space and Advanced Technology
OFII	Office of Finance and Insurance Industries
OFT	Orbital Flight Test
OGS	Optical Ground Station
OLI	Operational Land Imager
OMI	Ozone Monitoring Instrument
OPIR	Overhead Persistent Infrared
OPP	Office of Polar Programs
ORNL	Oak Ridge National Laboratory
ORS-6	Operationally Responsive Space-6
OSIRIS-REx	Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer
OSMRE	Office of Surface Mining Reclamation and Enforcement
OT&E	Operational Testing and Evaluation
OTM	Office of Transportation and Machinery

P

P&E	Physical and Environmental
P&P	Policy and Procedures
Pb	lead
PBN	Performance Based Navigation
PBS	Plum Brook Station
PCM	Post Certification Mission
PEA	partial economic area
PeV	petaelectronvolt
PFCS	Pump Flow Control Subassembly
PFM	probabilistic fracture mechanics
PHY	Division of Physics
PL&HA	Precision Landing and Hazard Avoidance
PLACE	Patterns in the Landscape–Analyses of Cause and Effect
PM	particulate matter
PMNS	Pontecorvo-Maki-Nakagawa-Sakata
PNT	Positioning, Navigation, and Timing
POES	Polar-orbiting Operational Environmental Satellites
PPA	Plasma Pyrolysis Assembly
PPE	Power and Propulsion Element
PREEVENTS	Prediction and Resilience against Extreme Events
PRISM	Parameter-elevation Regressions on Independent Slopes Model
PRS	Public Regulated Service
PSD	Planetary Science Division; production, supply, and distribution
PSP	Parker Solar Probe
PTD	Pathfinder Technology Demonstrator
PTES	Protected Tactical Enterprise Service
Pu	plutonium

Q

QueSST	Quiet Supersonic Technology

R

RAF	Royal Air Force
RCF	Range Communications Facility
REALM	RFID-Enabled Autonomous Logistics Management
REDDI	Research, Development, Demonstration, and Infusion
RF	Radio Frequency; Random Forest
RFE	Recursive Feature Elimination
RFI	Request for Information
RFID	Radio Frequency Identification
RFMG	Radio Frequency Mass Gauge
RFP	Request for Proposals
RHIC	Relativistic Heavy Ion Collider
RMA	Risk Management Agency
RNAV	Area Navigation
RNP	Required Navigation Performance
RO	radio occultation
ROS	rain-on-snow
ROSES	Research Opportunities in Space and Earth Sciences
RPS	radioisotope power system
RPT	Rocket Propulsion Testing
RR-7	Rodent Research-7
RRM	Robotic Refueling Mission
RSCC	Remote Sensing Coordinating Committee
RTL	register-transfer level

S

SABRS	Space and Atmospheric Burst Reporting System
SAE	Society of Automotive Engineers
SAM	Spacecraft Atmosphere Monitor
SAO	Smithsonian Astrophysical Observatory
SAR	Search and Rescue; Synthetic Aperture Radar
SATCOM	Satellite Communications
SAW	Spanwise Adaptive Wing
SBEM	Space Based Environmental Monitoring
SBIR	Small Business Innovative Research
SBIRS	Space Based Infrared System
SC	Office of Science
SCaN	Space Communications and Navigation
SCAN	Soil Climate
SCOAPE	Satellite Continental and Oceanic Atmospheric Pollution Experiment
SCS	Soil Conservation Service
SDB II	Small Diameter Bomb II
SDD	System Development and Demonstration
SDI	Space Data Integrator
SDO	Solar Dynamics Observatory
SEP	Solar Electric Propulsion
SFS	Space and Flight Support
SGSS	SN Ground Sustainment System
ShadowOC	Shadow Operations Center
SHARAD	Shallow Subsurface Radar
SHIIVER	Structural Heat Intercept, Insulation Vibration Evaluation Rig
SI	International System of Units
SIA	Satellite Imagery Archive

SLM	Selective Laser Manufacturing
SLS	Space Launch System
SLPSRA	Space Life and Physical Sciences Research and Applications
SMA	Submillimeter Array
SMAP	Soil Moisture Active Passive
SMC	Space and Missile Systems Center
SMCRA	Surface Mining Control and Reclamation Act of 1977
SMD	Science Mission Directorate
SN	Space Network
SNL	Sandia National Laboratories
SNOTEL	Snow Survey Telemetry
SNP	Saguaro National Park
SNSPD	superconducting nanowire single photon detector
SO_2	sulfur dioxide
SOA	service-oriented architecture
SOC	Space Optical Clock
SOHO	Solar and Heliospheric Observatory
Space RCO	Space Rapid Capabilities Office
SpaceX	Space Exploration Holdings, LLC
SPD	Space Policy Directives; supersonic particle deposition
SPLICE	Safe and Precise Landing—Integrated Capabilities Evolution
SPT	South Pole Telescope
SPUD	Small Polarimeter Upgrade for Degree Angular Scale Interferometer
SQUID	superconducting quantum interference device
sRLV	Suborbital Reusable Launch Vehicle
SSA	Space Situational Awareness
SSC	Stennis Space Center
SSDP	Space Security and Defense Program
SSEBop	Operational Simplified Surface Energy Balance
SSL	Space Systems Loral
SSMIS	Special Sensor Microwave Imager/Sounder
SSN	Space Surveillance Network
SSTI	Small Spacecraft Technology Initiative
SSTP	Small Spacecraft Technology Program
SSV	Space Service Volume
STARS	Standard Terminal Automation Replacement System
STELR	Supersonic Turbine Engine for Long Range
STEM	science, technology, engineering, and mathematics
STEREO-A	Solar and Terrestrial Relations Observatory–A
STEVE	Strong Thermal Emission Velocity Enhancement
STM	Space Traffic Management
STMD	Space Technology Mission Directorate
STP	Space Test Program
STRG	Space Technology Research Grants
STS	Space Transportation System
STSC	Scientific and Technical Subcommittee
STTR	Small Business Technology Transfer
SuMIRE	Subaru Measurement of Images and Redshifts
Suomi NPP	Suomi National Polar-orbiting Partnership
SURF	Synchrotron Ultraviolet Radiation Facility
SW	software
SWAMP	System-Wide Assessment and Monitoring Program
SWEAP	Solar Wind Electrons Alphas and Protons
SWFO	Space Weather Follow On
SWIM	System Wide Information Management

SWORM	Space Weather Operations, Research, and Mitigation
SWR	Space Weather Research
SWSH	Space Weather, Security, and Hazards

T

TACTOM	Tactical Tomahawk/Block IV
TAMR	Terminal Automation Modernization and Replacement
TAP	Traffic Aware Planner
TASAR	Traffic Aware Strategic Aircrew Requests
TBFM	Time Based Flow Management
TBO	Trajectory Based Operations
TCC	Tree Canopy Cover
TCCON	Total Column Carbon Observing Network
TDM	Technology Demonstration Mission
TDRS	Tracking and Data Relay Satellites
TECRO	Taipei Economic and Cultural Representative Office
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
THEMIS	Time History of Events and Macroscale Interactions during Substorms
TM	Thematic Mapper
TMA	telescope mount assembly
TOP	Texas Orthoimagery Program
TOPEX	Ocean Topography Experiment
TRACON	terminal radar approach control
TRISH	Translational Research Institute for Space Health
TSAS	Terminal Sequencing and Spacing
TSIS	Total and Spectral solar Irradiance Sensor
TT&C	telemetry, tracking, and communication
TTPs	Tactics, Techniques and Procedures
TUI	Tethers Unlimited, Inc.

U

UAE	United Arab Emirates
UAM	Urban Air Mobility
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
UDOP	User Defined Operational Picture
ULA	United Launch Alliance
UMFUS	Upper Microwave Flexible Use Service
UN	United Nations
UNISPACE+50	50th anniversary of the first United Nations Conference on the Exploration and Peaceful Uses of Outer Space
UNP	University Nanosat Program
USA	United States Army
USACE	U.S. Army Corps of Engineers

USAF	United States Air Force
US-COMP	Institute for Ultra-Strong Composites by Computational Design
USDA	United States Department of Agriculture
USEPA	U.S. Environmental Protection Agency
USFS	U.S. Forest Service
USG	U.S. Government
USGS	U.S. Geological Survey
USMC	United States Marine Corps
USN	United States Navy
USNDS	U.S. Nuclear Detonation Detection System
USSTRATCOM	United States Strategic Command

V

VAFB	Vandenberg Air Force Base
VASIMR	Variable Specific Impulse Magnetoplasma Rocket
VCLS	Venture Class Launch Services
VIIRS	Visible Infrared Imaging Radiometer Suite
VIP	Vegetation Inventory Program
VSWIR	visible-to-shortwave-infrared

W

WASDE	World Agricultural Supply and Demand Estimates
Webb	James Webb Space Telescope
WGS	Wideband Global Satellite Communications
WIN	Written Impact Narratives
WMN	Western-Range Modernization of Network
WSF	Weather Satellite Follow-on
WSF-M	WSF–Microwave
WSTF	White Sands Test Facility
WV2	WorldView-2

Y

YB	ytterbium

Z

ZBLAN	glasses with composition **Z**rF_4–**B**aF_2–**L**aF_3–**A**lF_3–**N**aF
ZBOT	Zero Boil-Off Tank
ZTF	Zwicky Transient Facility

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