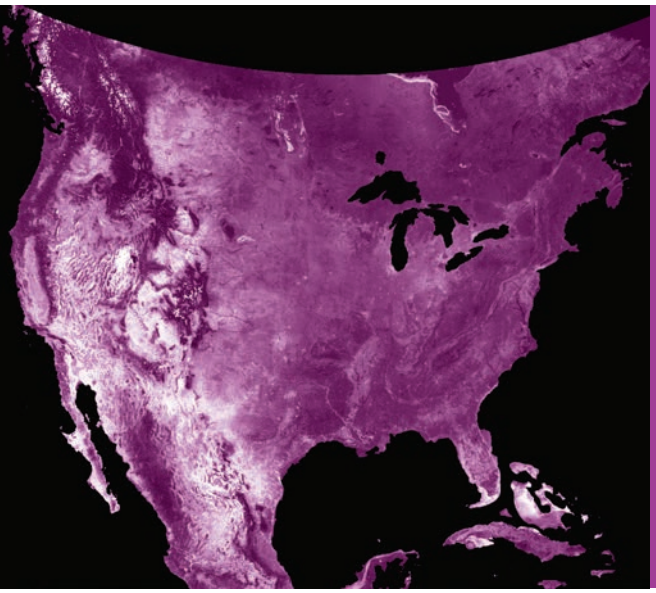
Aeronautics and Space Report of the President



Fiscal Year 2016 Activities

Aeronautics and Space Report
OF THE PRESIDENT

Fiscal Year 2016
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, 2015, through September 30, 2016. 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.** Composite image of the diffuse nebula NGC 6357 containing x-ray data from NASA's Chandra X-ray Observatory and the ROentgen SATellite (ROSAT) telescope (purple), infrared data from NASA's Spitzer Space Telescope (orange), and optical data from the SuperCosmos Sky Survey (blue) made by the United Kingdom Infrared Telescope (UKIRT). Credit: X-ray—NASA/CXC/PSU/L. Townsley et al.; optical—UKIRT; infrared—NASA/Jet Propulsion Laboratory–Caltech. **2.** Artist's concept of one of the eight Cyclone Global Navigation Satellite System satellites deployed in space above a hurricane. Credit: NASA. **3.** The Bigelow Expandable Activity Module (BEAM), installed on the International Space Station on April 16, 2016, at 5:36 a.m. EDT. Credit: NASA. **4.** Composite image, made from ten frames, showing the International Space Station in silhouette as it transits the sun at roughly five miles per second on December 17, 2016, from Newbury Park, California. Credit: NASA/Joel Kowsky. **5.** Artist's concept of NASA's Future X-57 Maxwell All-Electric Aircraft. Credit: NASA. **6.** Completion of James Webb Space Telescope center of curvature pre-test. Credit: NASA/Chris Gunn.

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National Aeronautics and Space Administration

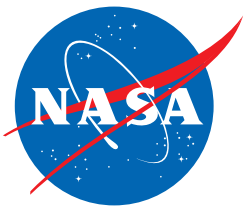
NASA

Human Exploration and Operations Mission Directorate

Exploration Systems Development

The Exploration Systems Development (ESD) programs—Space Launch System (SLS), Orion, and Ground Systems Development and Operations (GSDO)—represent an integrated effort to enable a deep space exploration capability for the Nation. SLS is a large launch vehicle for a new era of exploration beyond Earth's orbit; it will be capable of launching substantial cargo and, in the Orion spacecraft, astronauts on missions to deep space. These exploration systems also open new possibilities for other payloads that might be able to take advantage of these unique capabilities.

Orion and GSDO completed their Critical Design Review (CDR) in the first quarter of fiscal year (FY) 2016—commencing the programs' final design and fabrication phases. Also, SLS successfully completed the first hot-fire testing of an SLS RS-25 flight engine. The National Aeronautics and Space Administration's (NASA) strategic international partner, the European Space Agency (ESA), also reached important milestones, including the delivery of the European Service Module primary structure to ESA's primary assembly facility in Bremen, Germany.



Orion Program

The Orion Program successfully completed its CDR in the first quarter of FY 2016, demonstrating the level of program maturity needed to continue with

the final design and fabrication phase. Following Orion's successful CDR, primary pressure vessel welding was completed during the second quarter of FY 2016 for the Orion Crew Module at the Michoud Assembly Facility in Louisiana.

The Crew Module was delivered to Kennedy Space Center (KSC) in Florida for assembly, test, launch, and operations (ATLO). While at KSC, the Crew Module passed an important pressure proof test, ensuring the primary vessel's structural integrity in order to protect the crew's atmosphere against the vacuum of space. Orion's Crew Module assembly subsequently proceeded to secondary structures, brackets, and the first components. Harness integration and propulsion piping assembly commenced in the fourth quarter. Also in the fourth quarter, the Crew Module was moved into KSC's clean room at the Neil Armstrong Operations and Checkout Building, where welding has commenced on environmental and propulsion tubing. In addition, the first solar array wing deployment test was completed at Glenn Research Center's (GRC) Plum Brook Station (PBS) in Sandusky, Ohio. Development and qualification landing testing was concluded at Langley Research Center (LaRC) in Virginia with a total of ten tests.

NASA's strategic international Orion partner, ESA, delivered the European Service Module primary structure to Bremen, Germany, for assembly in the third quarter of FY 2016. In addition, the European Service Module Structural Test Article (E-STA) was delivered to PBS in the first quarter of FY 2016. At PBS, E-STA was mated with United States–based components of the Service Module, including the Crew Module Adapter (CMA) and Service Module Adapter (SMA) for acoustic, vibration, and shock testing. Orion technicians have started the installation process of the aft composite structure walls for the CMA. The E-STA test team completed the final set of vertical, partially filled tank configuration vibration tests in PBS's Mechanical Vibration Facility. Final preparations for acoustic testing in the third quarter of FY 2016 were under way at the time of preparing this report.

Space Launch System Program

The SLS Program made substantial progress in FY 2016 by successfully completing the first hot-fire testing of an SLS RS-25 flight engine. The test ran its full duration of 500 seconds and met all test objectives, including flight acceptance for a high-pressure fuel turbopump. The SLS Program also completed the second of

two full-duration hot-fire tests of the full-scale SLS five-segment booster qualification motor in the third quarter of FY 2016. During the test, 82 qualification test objectives were measured through more than 530 instrumentation channels on the booster at a cold motor conditioning temperature of 40 degrees Fahrenheit, which is the colder end of its accepted propellant temperature range. Preliminary analysis indicates that the instrumentation performance exceeded the test objective criteria.

The SLS Program also successfully completed manufacturing the Interim Cryogenic Propulsion Stage (ICPS) structural test article (STA). The ICPS STA will be tested in an integrated assembly, which will be subjected to structural loads and stresses to validate the analytical models of the flight hardware. In addition, the SLS Program finalized major structural modifications to retrofit the legacy Pegasus transportation barge for the Space Shuttle's external tanks in order to accommodate the SLS's larger core stage. Pegasus will transport the SLS core stage from its fabrication at the Michoud Assembly Facility to Stennis Space Center for green-run hot-fire testing and subsequently to KSC for flight integration and launch.

Ground Systems Development and Operations Program

Modernization and compatibility efforts for the Ground Systems Development and Operations Program continued in FY 2016. GSDO successfully completed its CDR during the first quarter of FY 2016, demonstrating the level of program maturity needed to continue with the final design and fabrication phase.

GSDO remains on track to receive the Mobile Launcher on Pad 39B in the fourth quarter of FY 2017. GSDO has initiated complex preparations at KSC for the SLS. These included the installation and testing of two J-level work platforms on the north and south sides of Vehicle Assembly Building High Bay 3, where the SLS will be prepared for launch. Upgrades to the Launch Pad 39B flame trench were also attained in FY 2016, including the installation of a new flame detector.

International Space Station

The International Space Station (ISS) continued its focus on research and technology development in such disciplines as biology, human research, biotechnology, Earth science, physical science, astrophysics, and satellite servicing during

FY 2016. Orbital ATK and SpaceX each completed two Commercial Resupply Services (CRS) flights. NASA installed the International Docking Adapter (IDA), which will allow the ISS to accommodate docking ports for visiting vehicles, enabling traffic flexibility and port redundancy for U.S.-operating-segment crew and cargo vehicle missions. NASA also installed the first commercially provided expandable module, called Bigelow Expandable Activity Module (BEAM), as a technology demonstration.

Three complete Soyuz crew rotations were accomplished in FY 2016. Soyuz 45S successfully launched to the ISS on December 15, 2015. Rendezvous and docking were completed successfully in manual mode after a failure message was received for a Soyuz thruster during final automated approach. Post-docking analysis showed that there was no thruster failure. Instead, pressure sensors inside the combustion chamber caused a false alarm. A change in this system with the new Soyuz MS vehicle design eliminates this failure mode, and both Soyuz 46S (March 18, 2016) and 47S (July 7, 2016) docked to the ISS without incident.

Four U.S. extravehicular activities (EVAs) were conducted during FY 2016. An EVA on December 21, 2015, was successfully completed to prepare for the arrival of the IDA. On January 15, 2016, an EVA to replace a failed voltage regulator ended early after a small water bubble was discovered in one of the helmets. Following extensive analysis of the issue, EVAs successfully resumed in August 2016, with two EVAs conducted that successfully completed the installation of the IDA, among other maintenance and science objectives.

On May 16, 2016, several CubeSats were deployed from the ISS, including St. Thomas More School Cathedral Satellite–1 (STMSat-1), the first CubeSat built by elementary school students to be deployed in space. The students involved were from St. Thomas More Cathedral School in Arlington, Virginia, and their proposal was selected under NASA's CubeSat Launch Initiative. STMSat-1 was launched to the ISS on December 6, 2015, aboard an Orbital ATK (OA) Cygnus cargo resupply spacecraft as part of NASA's Educational Launch of Nanosatellites (ELaNa) IX mission.

OA's fourth contracted cargo mission, OA-4, arrived at the ISS on December 9, 2015, following a December 6, 2015, launch on an Atlas V rocket from Cape Canaveral Air Force Station in Florida, and it departed from the ISS on February

19, 2016. Experiments delivered on Cygnus supported NASA and other research investigations during Expeditions 45 and 46 in areas such as biology, biotechnology, and physical and Earth science.

OA launched its fifth contracted cargo mission, OA-6, to the ISS on March 22, 2016. The Cygnus spacecraft was berthed at the ISS on March 26, 2016, delivering more than 7,700 pounds of science and research, crew supplies, and vehicle hardware. The spacecraft came equipped with the NanoRacks External Cygnus Deployer for CubeSats, which enabled the deployment of the satellites after the spacecraft had completed its cargo mission and left the ISS. Cygnus departed the ISS on June 14, 2016. After Cygnus was a safe distance away, ground controllers conducted the Spacecraft Fire Experiment–1 (Saffire-1), which provided an opportunity to study a large fire aboard a spacecraft for the first time. Data from the experiment will help NASA ensure the effectiveness of spacecraft fire safety systems on future missions.

SpaceX launched its eighth contracted cargo mission, SpX-8, to the ISS on April 8, 2016. The Dragon spacecraft was berthed to the ISS on April 10, 2016. The spacecraft delivered almost 7,000 pounds of cargo, including BEAM. Dragon's scientific cargo will support research in muscle atrophy, fluid dynamics at the atomic level, and protein crystal growth. Dragon departed the ISS and splashed down on May 11, 2016, returning more than 3,700 pounds of NASA cargo and science samples from a variety of technological and biological studies.

BEAM is designed to test expandable habitat modules in space. The module was installed on the ISS on April 16, 2016, and, after only partially expanding on May 26, 2016, BEAM was fully expanded on May 28, 2016. The module, roughly 10 feet in diameter and 13 feet long, will be attached to the ISS for about two years, during which time astronauts will enter the module for a few hours several times a year to retrieve sensor data and assess conditions. Expandable habitats are designed to take up less room on a launch vehicle but provide greater volume for living and working in space once expanded. This first in situ test of the module will allow investigators to gauge how well the habitat protects against solar radiation, space debris, and contamination.

SpaceX-9 launched on July 18, 2016, carrying the International Docking Adapter, as well as nearly 5,000 pounds of supplies and payload, including critical

materials to directly support dozens of science and research investigations. After a fully successful mission, the Dragon capsule splashed down in the Pacific Ocean, returning more than 3,000 pounds of NASA cargo and science samples, including materials from the Heart Cells study, which investigated how heart muscle tissue contracts, grows, and changes in microgravity. Knowledge gained from the experiment may help advance the study of heart disease on Earth.

Space Life and Physical Sciences Research and Applications

Human Research Program

In 2016, NASA completed the flight phase of the ISS One-Year Mission and ISS Twins Study. Astronaut Scott Kelly and cosmonaut Mikhail Kornienko completed the ISS One-Year Mission: the longest space mission ever undertaken by a U.S. astronaut. As part of this major international effort, the Human Research Program (HRP) developed the U.S.–Russian joint biomedical research plan that included ISS studies on ocular health and body fluid shifts, immune and cardiovascular systems, cognitive performance testing, and effectiveness of countermeasures against bone and muscle loss. During the One-Year Mission, NASA also conducted the ISS Twins Study. This study of identical twin astronauts Scott Kelly and retired astronaut Mark Kelly is the first human genomics study associated with astronauts and provided an unprecedented opportunity to study the effects of spaceflight on the human body at the genetic level. To undertake this research, NASA formed an innovative team of leading genetics and genome experts to explore the effects and changes that may occur in spaceflight (compared to on Earth). This pioneering study will provide new genetics data on the effects of spaceflight on the entire complement of biomolecules, such as proteins (proteomics) and genes (genomics), opening possibilities for the development of new precision-medicine approaches to countermeasures and the next-generation genomics solutions to mitigate crew health and performance risks.

NASA launched a Translational Research Institute charged with researching and developing innovative approaches to reducing risks to humans during long-duration exploration missions, including NASA's Journey to Mars. The Center for Space Medicine at Baylor College of Medicine was awarded a grant to develop and

implement this institute, which includes the Massachusetts Institute of Technology (MIT) and the California Institute of Technology (Caltech) as partners. Translational research is an interdisciplinary model of research that focuses on rapidly translating fundamental research concepts into practice, thereby generating tangible health outcomes—in this case, for astronauts. This new institute will expand research leadership in translational human performance, biomedical, environmental, cognitive, and behavioral science. It will also catalyze greater involvement of the broader science community in accomplishing the Agency's human exploration goals. Results or methods derived from laboratory experiments or clinical trials will be translated to point-of-care astronaut health and performance applications, using a bench-to-spaceflight model. In this way, the institute will rapidly produce promising new approaches, treatments, countermeasures, or technologies that have practical applications for spaceflight. The Translational Research Institute is a key component of NASA's strategy for reducing human exploration health and performance risks for the next generation of space exploration.

ISS Research—Biological and Physical Sciences

The Space Biology Program (SBP) made significant progress in its aim to increase the relevance of spaceflight research by making a large body of data accessible and relevant to the global science community through the continuation of the GeneLab Project. The GeneLab Data System, which can be accessed at *http://genelab.nasa.gov*, now houses 80 datasets, which are meticulously curated and fully accessible to the public: 47 of these studies are from spaceflight experiments, and 33 are from relevant ground experiments. All contain novel genomic, proteomic, or metabolomics data for download and immediate use by the scientific community. GeneLab is currently averaging more than 1,000 file downloads per month, with a data volume of roughly three terabytes per month, served up to 35 different countries.

GeneLab released an Innovation Awards Research Announcement (NRA NNH16ZTT001N-GL) in March 2016, which garnered 34 responses. Final programmatic review is complete.

The Space Biology Program continues to make significant progress in implementing key recommendations of the National Research Council (NRC) Decadal Survey,

particularly in plant biology and microbiology. Seventy-two SBP research tasks are in various stages of completion. Important new studies are being developed for flight on the ISS, in ground-based simulations, and on other spaceflight platforms. Among these are multi-investigator science teams that have designed experiments to measure important physiological and multi-omic biological responses to spaceflight that will contribute baseline data to the GeneLab Project database to honor SBP's commitment to providing complete, open access to science data.

In partnership with the Human Research Program, SBP projects are building knowledge that is key to the future production of nutritious fresh food in space through the continuation of the Vegetable Production System (Veggie) hardware system on orbit. In 2016, the Veggie hardware demonstrated the ability to cultivate nutrient-dense and environment-enriching lettuces and flowers on board the ISS. SBP and HRP jointly sponsored biological studies in the area of artificial gravity research. This research is being initiated to answer important questions about how biological systems respond to changes in the gravitational field and to simulated Mars and moon gravitational loading.

SBP established a Space Act Agreement with the Alfred P. Sloan Foundation to enable research in the Microbiology of the Built Environment (MoBE) area from potential postdoctoral students who will study ISS microbial isolates from the Life Sciences Data Archive. Each partner will fund two postdoctoral fellows.

SBP continued the Microbial Tracking project in 2016 to respond to a high-priority recommendation, made by the National Research Council's 2011 Decadal Survey for space life and physical sciences, to conduct an integrated "microbial observatory" investigation of the evolving microbiome of the ISS. The three-flight series of Microbial Tracking–1, which investigated airborne and surface populations of microorganisms aboard the ISS, was fully executed in 2016. In this study, investigators found a unique fungal isolate of *Aspergillus fumigatus*. Virulence assessment revealed that the ISS isolates were significantly more lethal than clinical strains. These studies included complete genetic/genomic characterization that is being deposited in the GeneLab Database as the studies are completed. Studies such as these are important because understanding the microbiome of a spacecraft and how microbes adapt to spaceflight is critical to enabling future human exploration missions. New research projects jointly supported by SBP and Physical

Sciences will also examine the effects of microbial biofilms occurring in spaceflight on materials used to build exploration vehicles.

The Physical Sciences Program continues to make significant progress in implementing key recommendations of the NRC Decadal Survey. The Cold Atom Laboratory (CAL), a project that aims to create the lowest measurable temperature in the universe aboard the ISS in a facility intended to support a range of world-class investigations in atomic physics, is completing its final integration and testing on its way to a planned 2017 launch. In a paper published in the journal *Science* in August 2015, CAL science team member Holger Mueller (a physicist at the University of California, Berkeley) and colleagues highlighted the possibility of using observations of atomic physics in ultra-cold facilities like CAL to directly observe dark energy, which accelerates the expansion of the universe. The nature of dark energy is one of the greatest mysteries in physics and cosmology. In 2016, Mueller and coworkers continued to advance relevant theories and conduct experiments to search for a broad class of dark-energy particles.

The vision of MaterialsLab is to fully utilize the ISS as a national laboratory to conduct microgravity materials science and disseminate data into open science informatics in order to accelerate the revelation of materials science mysteries; develop engineering-need-driven higher-performing materials for NASA and the United States; and enhance education in science, technology, engineering, and mathematics (STEM). In support of this goal, NASA selected 16 proposals to help define seven high-content reference experiments covering the following disciplines: thermophysical properties; materials processes that affect microstructure, composition, and other characteristics; biophysics, specifically biomaterials and biofilms; and liquid crystals.

NASA Physical Sciences populated the Physical Sciences Informatics database, which can be accessed at *http://psi.nasa.gov*, with the raw data from more than three dozen flight experiments. In an effort to stimulate broader use of flight results by the research community, NASA released two NASA Research Announcements (NRAs) specifically inviting research projects based on the analysis of this archived flight experiment data. In 2016, NASA selected ten proposals from these first two NRAs, and a third NRA was released in September 2016.

Commercial Crew Program

During the fiscal year, the Commercial Crew Program (CCP) partners Boeing and SpaceX continued making technical and programmatic progress in maturing their respective commercial crew transportation systems.

- Boeing completed its Critical Design Reviews (CDRs), a major Commercial Crew Transportation Capability (CCtCap) contract milestone.
- Throughout the year, both partners continued identifying and submitting variances, alternate standards, and hazard reports necessary for NASA's crew transportation system certification efforts.
- Boeing conducted modifications to Cape Canaveral Air Force Station's Launch Pad 41 and performed several wind tunnel and landing tests.
- SpaceX completed its delta CDR, a key milestone in integrated crew transportation design process.
- Both partners have begun manufacturing qualification hardware as well as the flight systems they will use for their ISS demonstration missions.

Through the CCP, NASA is ensuring that the Agency's commercial partners' crew transportation systems are safe, reliable, and cost-effective. The certification process assesses progress throughout the production and testing of the partners' systems, which include the launch vehicle, the spacecraft, and ground 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.

Advanced Exploration Systems

The Advanced Exploration Systems (AES) Division is pioneering 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 2016, the AES Division continued the successful execution of 28 research and technology development activities employing 451 civil servants spread across all NASA Centers. In FY 2016, AES had a goal to complete at least 80 percent of the 66 annual milestones. The team accomplished 47 milestones (71 percent) on schedule and with the available resources. The remaining milestones either were delayed or could not be accomplished due to budget reductions, dependencies on other programs, or technical issues.

In May 2016, the BEAM was deployed on the ISS. BEAM was developed in partnership with Bigelow Aerospace, and it is demonstrating inflatable structures technology that could be used for future habitats in cislunar space or in low-Earth orbit. During its two-year mission, sensors inside BEAM will characterize structural dynamics, orbital debris impacts, temperature, and radiation levels.

AES completed Phase 1 Next Space Technology for Exploration Partnerships (NextSTEP) studies with Bigelow Aerospace, Boeing, Lockheed Martin, and Orbital ATK to define system requirements and design concepts for deep space habitats. The Phase 1 partnerships required at least 50 percent cost sharing from industry. These initial studies helped the companies formulate their proposals for Phase 2.

In April 2016, NASA issued a second NextSTEP Broad Agency Announcement to provide an opportunity for additional partners to develop full-scale prototype habitats by 2018 for integrated ground testing. In August 2016, Phase 2 habitat development partnerships were awarded to the original four Phase 1 companies plus Sierra Nevada Corporation and NanoRacks. The Phase 2 partnerships require at least 30 percent cost sharing from industry. In Phase 2, NASA, its international partners, and the industry will work together to develop system interface and design standards to ensure that habitation elements from different providers can be assembled together.

Supporting the NextSTEP commercial partnerships are internal AES activities that are developing technologies for life-support systems, radiation protection, logistics reduction, avionics and software, autonomous mission operations, and spacecraft fire safety.

The AES Life Support Systems activity completed the Systems Design Review for the Spacecraft Atmosphere Monitor that will detect contaminants in the air

inside the ISS. The project also delivered an Aerosol Sampler for launch to the ISS to detect small particles in the air.

Under the NextSTEP Life Support Systems activity, Orbitec built a prototype plant growth unit for augmenting conventional life-support systems in a habitat, and United Technology Aerospace Systems developed a modular life-support systems architecture.

In June 2016, AES conducted the Saffire-I spacecraft fire safety experiment on board the Cygnus vehicle to investigate the spread of large fires in microgravity. The experiment ignited a representative material sample and recorded the spread of the flame on video. It was found that the flame spread slower than predicted. The Saffire-II experiment that will investigate the flammability of different materials launched in October 2016.

The AES Radiation Sensors activity delivered a Fast Neutron Spectrometer for launch to the ISS. This instrument will measure the secondary neutrons that are generated when charged particles collide with the spacecraft structure. In addition, the CDR for the radiation detectors that will be flown on EM-1 was completed.

AES's Autonomous Systems and Operations activity demonstrated software to automate the powering up of an EXpedite the PRocessing of Experiments for Space Station (EXPRESS) rack on the ISS, which will reduce the crew time needed for routine operations.

The AES Avionics and Software activity conducted a mission simulation of Orion docking with a deep space habitat using an integrated avionics, power, and communications architecture.

AES installed Disruption Tolerant Networking (DTN) software on the ISS to improve the efficiency of space-to-ground communications and began interoperability testing between the Korea Aerospace Research Institute and the DTN Engineering Network.

The AES Logistics Reduction activity installed a repurposed Multi-Purpose Cargo Transfer Bag around the treadmill on the ISS to provide acoustic insulation. AES also delivered radio-frequency identification tag readers to track and autonomously manage inventory on the ISS.

The AES In-Space Manufacturing activity completed the fabrication of an in-space recycler that will produce feedstock for a 3D printer from discarded plastic parts and trash.

The AES Synthetic Biology Applications activity demonstrated that yeast cells can be genetically engineered to produce the bionutrients that astronauts will need on long-duration missions.

AES is pursuing robotic precursor missions to characterize the environments, the hazards, and the availability of resources on the moon, near-Earth asteroids, and Mars in preparation for future human exploration.

Working with NASA's Science Mission Directorate (SMD) and Space Technology Mission Directorate (STMD), AES developed preliminary designs for three payloads on the Mars 2020 rover to address strategic knowledge gaps for human exploration. The Mars Oxygen In Situ Resource Utilization Experiment (MOXIE) will demonstrate the production of oxygen from the Martian atmosphere to enable in situ propellant production for future human missions. The Mars Environmental Dynamics Analyzer (MEDA) is a surface weather station that will measure temperature, pressure, winds, and dust to characterize the environmental conditions that may be encountered by human explorers. Both MOXIE and MEDA completed their Preliminary Design Reviews. In addition, AES is re-flying the Mars Entry, Descent, and Landing Instrumentation (MEDLI) experiment to further characterize the entry environment for future landings on Mars by robotic and human missions. The MEDLI-2 project completed arcjet testing of the thermal protection system with embedded temperature and pressure sensors.

AES continued the development of three CubeSats that will be launched as secondary payloads on EM-1. The payloads include BioSentinel, which will investigate the effects of deep space radiation on yeast DNA; the Lunar Flashlight, which will search for volatiles in shadowed craters on the moon; and the Near-Earth Asteroid (NEA) Scout, which will use a solar sail to fly by an asteroid. BioSentinel completed its CDR, and the Lunar Flashlight and NEA Scout completed their initial safety reviews and design reviews.

AES's Lunar Cargo Transportation and Landing by Soft Touchdown (Lunar CATALYST) activity continued to work with three commercial partners to develop lunar landers for delivering small payloads. NASA is providing engineering

expertise, test facilities, software, and loaned hardware to the partners. In 2016, Moon Express completed its Preliminary Design Review and received a favorable payload determination from the Federal Aviation Administration (FAA).

The AES Resource Prospector continued mission-formulation activities this year. AES completed a six-month study with Taiwan to develop design concepts for the Resource Prospector lander and conducted environmental tests of major subsystems.

In September 2016, AES issued an Announcement of Opportunity for an instrument to be hosted on the Korea Pathfinder Lunar Orbiter to measure lunar volatiles.

Under the NextSTEP Advanced Propulsion activity, Ad Astra Rocket Company assembled subsystems and upgraded test facilities to prepare for the testing of a Variable Specific Impulse Magnetoplasma Rocket (VASIMR). MSNW demonstrated pulsed operation of a plasma thruster.

AES matured the Evolvable Mars Campaign (EMC) series of human exploration architecture studies beyond encompassing the capabilities of the ISS, Orion, SLS, cislunar habitation, and Asteroid Redirect Mission (ARM) to include a broader scope with Agency-wide participation and cooperative Mars mission planning with the SMD. The campaign included the analysis of capabilities realized through the NextSTEP habitation and life-support systems studies, along with emerging cislunar habitation plans of our international partners. The EMC cislunar habitation concepts focused on future architectures reflecting ongoing technology investments and commercial capabilities at minimum cost and risk for human spaceflight missions with maximum benefits for human exploration.

Launch Services

During FY 2016, the Launch Services Program (LSP) successfully launched two major science missions: Jason-3 and the Origins, Spectral Interpretation, Resource Identification, Security–Regolith Explorer (OSIRIS-REx). Jason-3 successfully launched on January 17, 2016, aboard a Falcon 9 version 1.1 rocket from Vandenberg Air Force Base in California. Prior to conducting the Jason-3 launch, SpaceX had experienced a launch failure on the 14th flight of the Falcon 9 version 1.1 launch

vehicle during a cargo resupply mission to the ISS on June 28, 2015. In addition to participating as part of the SpaceX Accident Investigation Team (AIT), LSP conducted its own independent review of the launch failure and was designated the Agency's lead to perform this function. The investigation ran from July 2015 to November 2015 and resulted in the successful return to flight of the Falcon 9 version 1.1 launch vehicle for Jason-3. OSIRIS-REx launched on September 8, 2016, aboard an Atlas V rocket from Cape Canaveral Air Force Station (CCAFS) in Florida. The LSP also continued to provide launch-related systems engineering, launch integration, and mission design and analysis support to over 40 NASA-sponsored missions in various phases of development. To learn more about these and other NASA science missions, see the Science Mission Directorate 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. In FY 2016, the program acquired launch services for one communications satellite and one future science mission: the Tracking and Data Relay Satellite (TDRS) M and Mars 2020. TDRS-M and Mars 2020 will both launch on United Launch Services' Atlas V rockets from CCAFS in Florida.

NASA and LSP also partnered with several universities to launch small research satellites through the Educational Launch of Nanosatellites project and the CubeSat Launch Initiative, which provides rideshare opportunities for small-satellite payloads to fly on upcoming launches when space is available. These partnerships provide educational opportunities for students in science, technology, engineering, and mathematics disciplines, thereby strengthening the Nation's future workforce. In addition, as CubeSats continue to play an increasingly larger role at NASA, LSP also awarded multiple Venture Class Launch Service (VCLS) contracts designed to create an alternative to the current rideshare approach and to foster a commercial launch market dedicated solely to flying small-satellite payloads. In FY 2016, VCLS contracts were awarded to Firefly Space Systems, Inc.; Rocket Lab USA; and Virgin Galactic, LLC, with the first demonstration launch scheduled for summer 2017. To date, CubeSats have been selected from 32 states across the United States, with 46 missions launched and 56 manifested on NASA,

National Reconnaissance Office, U.S. Air Force, and commercial missions. LSP is also conducting certification efforts for United Launch Alliance's Delta IV Heavy and SpaceX's Falcon 9 Full Thrust launch vehicles.

Lastly, LSP participated in SpaceX's investigation of the on-pad explosion that occurred on September 1, 2016, at Space Launch Complex 40 (SLC-40) at CCAFS in Florida during propellant loading of the Falcon 9 Full Thrust launch vehicle variant. The vehicle was being prepared for an on-pad engine test when the vehicle explosion occurred. While this accident did not occur in preparation for a NASA launch, the Agency wants to understand the incident and any design or procedure changes SpaceX elects to make before committing NASA payloads to fly on future Falcon 9 vehicles. LSP was a member of the SpaceX AIT and is also conducting its own independent review of the accident.

Human Spaceflight Capabilities

By the end of FY 2016, the Rocket Propulsion Test (RPT) Program had safely performed 540 tests. Test time totaled over 152,388 seconds, with more than 15,538 seconds of hot fire testing at various levels of thrust. This represents a 20 percent increase in testing and a 30 percent increase in test duration from FY 2015. During this period, the test facilities had three facility-caused test delays resulting in a 99.4 percent facility readiness, far exceeding the 90 percent RPT Annual Performance Indicator.

In FY 2016, Stennis Space Center (SSC) had several test programs under way, including RS-25 in support of the SLS Program, as well as flight certification testing for the Aerojet Rocketdyne RS-68 engine in support of the United States Air Force (USAF) and United Launch Alliance (ULA). Development testing continued for NASA's Morpheus lander, as well as subscale testing of the SpaceX Raptor engine. Refurbishment and repair activities continued on the restoration of the B-2 test stand for SLS core-stage testing; and other critical enabling infrastructure, such as replacing both the B leg and the A leg of the high-pressure industrial water system, were completed.

In 2016, there were several facility preparation activities under way to support multiple Aerojet Rocketdyne development activities, to include facility

modifications and structural test equipment (STE) development in E-1 Cell 1 supporting AR-1 Full-scale liquid oxygen (LOX)/refined propellant (Rp) Battleship Pre-burner testing. Additionally, there were preliminary engineering and design activities under way on A-2 in support of the AR-1 Engine System testing.

Other activities at SSC included the buildup of systems in the E-Complex required to support the joint Department of Defense (DOD)–NASA hydrocarbon boost program and the Aerojet Rocketdyne Liquid Oxygen (LOX) and Refined Petroleum (Rp) development program. USAF and NASA Advanced Booster Engineering Demonstration and/or Risk Reduction (ABEDRR)/Hydrocarbon Boost development activities, facility modifications, and STE development are under way on E-1 Cell 1 supporting the joint Hydrocarbon Boost testing. The facility's ready date and test article delivery are scheduled for October 2017; the testing schedule was still to be determined at the time of preparing this report. Additionally, facility preparations are under way at E-1 Cell 3 for the SpaceX Full Scale Raptor component.

Marshall Space Flight Center (MSFC) continued testing engine components manufactured using advanced technologies, including components built using select laser melting. In addition to testing the components manufactured using advanced technologies, MSFC tested articles using LOX, liquid methane (LCH_4), and new LOX Rp combustion techniques.

White Sands Test Facility (WSTF) continued the buildup and preparation of Test Stand 301 to support testing of the Orion ESA Service Module (SM) and began construction activities on Test Stand 301A to support the Boeing Company's CST-100 crew abort system and SM testing. In addition to the two SM programs, WSTF also provided test support for Boeing, the Missile Defense Agency (MDA), the USAF Minuteman, and the USAF Peacekeeper demilitarization.

Additionally in 2016, preparations were under way at WSTF to support the Commercial Crew Program for acceptance-testing the Launch Abort Engines (LAEs), Orbital Maneuvering Attitude Control (OMAC), and Reaction Control System (RCS) thrusters. TS-406 is being reactivated to support the RCS thrusters. TS-401 will be utilized for the OMAC thrusters. TS 301-A will be used for LAE testing.

At Glenn Research Center in 2016, the activation of the Altitude Combustion Stand (ACS) to perform small in-space chemical propulsion development testing

was completed. In July 2016, oxygen/methane igniter tests for Lander Technologies were successfully conducted.

At Plum Brook Station, preparations were under way for a B-2 characterization test using auxiliary injectors to pull the test-and-spray chamber to altitude and fire a small thruster (Morpheus Engine) for a limited time. The characterization test will include engine firings at ambient and simulated space environments.

The Asteroid Redirect Mission (ARM) was aimed at progressing certain technologies and capabilities needed for deep space exploration. ARM is led by the Human Exploration and Operations Mission Directorate (HEOMD) in partnership with the Space Technology Mission Directorate (STMD) and the Science Mission Directorate, leveraging the cross–Mission Directorate strengths of the Agency.

The plan for the robotic spacecraft was to use advanced solar electric propulsion (SEP). An electric propulsion team for STMD, led by GRC, continues certain technology development efforts. Specific work included solar-array systems technology development and testing, as well as wear and environmental testing of technology demonstration units of Hall effect thrusters with magnetic shielding. A contract for a commercial provider of the flight electric propulsion system to be demonstrated by NASA on the Asteroid Redirect Robotic Mission (ARRM) was awarded to Aerojet Rocketdyne in April 2016.

- A Standing Review Board was chartered to provide an independent review of the ARRM, including a cost and schedule assessment, to support an approval gate for the second phase of project formulation, Phase B. After successfully passing Key Decision Point (KDP)-B on July 15, 2016, the ARRM project received authorization to transition from Phase A to Phase B activities.
- Competitively selected spacecraft design studies were awarded to four commercial spacecraft bus subcontractors. The selected contractors, Boeing, Lockheed Martin, Orbital ATK, and Space Systems Loral, completed their studies in June 2016. These results were used to inform KDP-B and subsequent spacecraft procurement. The Request for Proposal for Phase 2 procurement of the ARRM spacecraft bus was then released by the Jet Propulsion Laboratory (JPL) to the four Phase 1 spacecraft bus study subcontractors in September. Spacecraft bus vendor selection is presently on hold depending on the future plans for ARRM technology.

ARM had also been engaged with potential strategic international partners. ARM entered into a study agreement with the Italian Space Agency (ASI) in FY 2016 to identify the feasibility of potential collaboration on ARRM. Discussions on potential collaboration were also held with the Canadian Space Agency (CSA) and the Japan Aerospace Exploration Agency (JAXA). The work from these partnerships will be redirected to other areas. As part of the NASA FY 2018 budget, ARM activities will no longer be continued. The work from ARM will be redirected to a power and propulsion bus as part of NASA's deep space infrastructure.

Space Communications and Navigation

The Space Communications and Navigation (SCaN) Program manages and operates NASA's space communications and tracking capabilities, which are required for successful crewed and robotic spaceflight launches and missions, both for NASA and for other Government agencies. SCaN provides a critical lifeline to astronauts and spacecraft; it uploads commands and essential crew instructions, retrieves health and safety and science data from spacecraft, and sends the data to individual mission control centers.

In FY 2016, SCaN remained focused on the critical sustainability and development of the ground and space components of the networks that provide space communications for NASA's missions. The three networks—the Near Earth Network (NEN), the Space Network (SN) Tracking and Data Relay Satellite System (TDRSS), and the Deep Space Network (DSN)—continued to meet the space communications needs, such as Earth monitoring and support of deep space science missions, of a wide range of customers, both internal and external to NASA. SCaN continued to surpass its requirement of 95 percent proficiency with at least 99 percent proficiency in all of its networks, providing communication and navigation services to all science and human missions.

During FY 2016, SCaN networks provided over 178,000 hours of tracking and more than 160,000 passes, as well as launch and early-orbit telemetry, tracking, and communication (TT&C) services to 26 Expendable Launch Vehicle (ELV), human spaceflight, and robotic missions.

As part of sustainment activity, SCaN initiated the preparation of the TDRS-M spacecraft for launch and coordinated with the Launch Services Program for an

August 2017 launch. Significant progress was made in the SN Ground Sustainment System project in the areas of coding, hardware integration, and testing. SCaN is continuing to address the cost and schedule challenges encountered in this major ground system upgrade activity.

SCaN continued to replenish networks to resolve ongoing obsolescence and to modernize the operational equipment. The program installed new antennas and radomes for the Launch Communications Stations (LCS) at Ponce de Leon (PDL) and Kennedy Uplink Station (KUS) in Florida in preparation for the Exploration-class missions and SN enhancements for EM-1 in advance of end-to-end testing with the Multi-Purpose Crew Vehicle (MPCV). SCaN completed one 34-meter antenna (DSS-36) at the Canberra Deep Space Communications Complex in Australia. Also, contracts were awarded and excavation has begun for two new 34-meter antennas at the Madrid Deep Space Communications Complex in Spain.

The SCaN Program has been developing and demonstrating optical communication technology through space with a long-term vision to operationalize such technology. This technology can increase data rates by an order of magnitude with lower spacecraft burden (mass, power, and volume) than the current radio-frequency-based systems. Due to its lower burden, it can also be applied in smallsat and nanosat applications. SCaN successfully completed CDRs for two Optical Ground Stations (OGSes)—OGS-1 at JPL and OGS-2 in Hawaii—and started implementation at both sites. SCaN secured an agreement with JAXA, France's Centre National d'Études Spatiales (CNES), and Japan's National Institute of Information and Communications Technology (NICT) to cooperate in developing a high-data-rate optical communications recommendation by spring 2017.

SCaN Spectrum Management continued to work with the White House, Congress, national regulators, and interagency partners in implementing the President's Broadband Initiative. As part of the State Department–led U.S. delegation to the World Radiocommunication Conference 2015 in Geneva, Switzerland, NASA successfully negotiated U.S. proposals on spectrum issues of interest and concern to NASA.

The development of space communication standards is critical for effective space communication. The SCaN Data Standard Project engages in an international organization known as the Consultative Committee for Space Data Systems

(CCSDS) to create space communication data standards. CCSDS was formed in 1982 by the major space agencies of the world to provide a forum for the discussion of common problems in the development and operation of space data systems. Space communications data standards enable the world's space agencies to provide cross support to each other and hence eliminate the need for each to build and deploy its own space and ground assets. Eliminating the need for additional space relay satellites or ground stations translates into hundreds of millions of dollars in savings for NASA without reducing services and coverage to space missions. In 2016, SCaN engineers led CCSDS working groups in completing many new standards and made substantial progress through leading the new working group chartered to develop standards for optical communications.

SCaN continued in its role as the Executive Director of the National Space-Based Positioning, Navigation, and Timing (PNT) Advisory Board, an august body of PNT experts from within industry and the international community. On behalf of the Agency, SCaN is leading the national effort to develop a Space Service Volume capacity for the Global Positioning System (GPS), which will enable the use of the side lobes of the GPS signal for beyond-low-Earth-orbit PNT services.

Science Mission Directorate

NASA's Science Mission Directorate (SMD) is driven by scientific questions about Earth, the sun, the solar system, and the universe. SMD manages an interconnected program, where discoveries in one scientific area can be directly related to other areas of study. Together with the Joint Agency Satellite Division (JASD) and the James Webb Space Telescope (JWST) program office, the four SMD research divisions provide the Nation with groundbreaking discoveries, innovative methods, and positive impacts across Earth and space science.

In FY 2016, NASA maintained a fleet of Earth-observing satellites and airborne assets that provided critical information to improve our understanding of severe weather events, natural disasters, and Earth's changing climate. The Agency launched the Jason-3 satellite on behalf of the National Oceanic and Atmospheric Administration (NOAA), the French Space Agency (Centre National d'Études Spatiales, or CNES), and the European Organisation for the Exploitation of

Meteorological Satellites (EUMETSAT) to monitor global sea level and provide new data on cloud cover and aerosols. NASA's Heliophysics Division provided daily imagery of the sun and collected new data to improve our understanding of solar phenomena in deep space and on Earth. It was an exciting year for the Planetary Science Division (PSD), with the arrival of the Juno mission at Jupiter, as well as new discoveries announced based on missions to Pluto, Saturn, and elsewhere. NASA continued to make exciting new discoveries with its three great astrophysics observatories: the Hubble Space Telescope, the Chandra X-ray Observatory, and the Spitzer Space Telescope. The JWST, the next great observatory in this illustrious line, continues integration and testing in preparation for a 2018 launch.

Earth Science Division

Earth is a complex, interconnected system changing on a variety of spatial and temporal scales in ways that impact everyday life, yet it is a system that we do not fully understand. NASA seeks to understand the following key science questions: How is the global Earth system changing? What causes these changes in the Earth system? How will the Earth system change in the future? How can Earth system science provide societal benefits? NASA's Earth Science Division (ESD) conducts a wide range of satellite and suborbital missions to observe Earth's land surface and interior, biosphere, atmosphere, cryosphere, and oceans as part of a program to improve understanding of Earth as an integrated system. Environmental data products derived from these observations are used in resource management as well as for a range of societal applications, including weather forecasts, climate projections, sea-level change, water management, disease early warning, agricultural production, and the response to natural disasters.

Several operational missions continue to collect data to better understand changes in the environment. The Orbiting Carbon Observatory-2 (OCO-2) measures carbon dioxide from the top of Earth's atmosphere to its surface, and scientists have been able to use data from the spacecraft to study both carbon emissions and carbon absorption worldwide. Scientists use measurements from the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Aqua satellite to better understand trends in water and ice, showing, for example, that

blooms of phytoplankton are becoming common around Greenland's coast as glacial meltwater delivers nutrients to coastal waters. NASA's Terra satellite revealed a growing rift along the Larsen C ice shelf in Antarctica, an event similar to that seen before the collapse of the Larsen B ice shelf in 2002. The Global Precipitation Measurement (GPM) mission, a joint mission between NASA and JAXA, monitors rainfall and severe storms across the globe.

Airborne campaigns have also made important contributions in the past year. The Atmospheric Carbon and Transport–America (ACT-America) campaign focused on the movement of carbon dioxide and methane in the atmosphere. The Atmospheric Tomography (ATom) airborne mission made detailed measurements of atmospheric chemistry that are difficult or impossible to make from space. NASA's ObseRvations of Aerosols above CLouds and their intEractionS (ORACLES) mission flew along the coast of Namibia to observe how tiny aerosol particles interact with clouds. The COral Reef Airborne Laboratory (CORAL) examined the condition of coral reefs, creating a database of uniform scale and quality.

In July 2016, NASA and the U.S. Agency for International Development (USAID) opened a new environmental monitoring program in West Africa to enhance the role of space-based observations in the management of environmental issues facing the world today. SERVIR[1]–West Africa, based in Niamey, Niger, is one of four NASA-USAID–sponsored centers operating in developing regions of the world. The SERVIR centers, which together serve more than 40 countries, allow scientists and decision makers to use publicly available data from space to manage a variety of critical regional issues, including food security, water resources, land-use change, and natural disasters. SERVIR was developed in coordination with the Group on Earth Observations, an alliance of more than 100 nations and organizations collaborating to build a global Earth-observing system.

ESD is also making steady progress in the development of new systems that will provide further insight into key scientific questions. The formulation phase for Landsat 9 was initiated with the goal of extending to half a century the Landsat program's record of continuous land-image collection. IceSat-2 and the Gravity Recovery and Climate Experiment (GRACE) Follow On missions—the latter a

1 See *https://www.servirglobal.net/#aboutservir* for a description.

partnership with Germany—are both planned to launch in FY 2018. Both met important milestones in the assembly and testing of flight hardware, in preparation for missions contributing to our understanding of changes in Earth's cryosphere and hydrosphere. The Cyclone Global Navigation Satellite System (CYGNSS), which launched on December 16, 2016, consists of eight small satellites that will make frequent and accurate measurements of ocean surface winds throughout the life cycle of tropical storms and hurricanes. Through this mission, NASA is demonstrating the potential of small satellites to contribute to important science goals. In addition to supporting small-satellite missions, NASA has made strategic investments in three Venture Class Launch Services companies, contracting for launch services designed to provide small satellites with access to low-Earth orbit.

Technology developments funded by ESD are enabling new capabilities to help scientists understand our home planet. For example, the ozone Differential Absorption Lidar (DIAL) instrument—a compact airborne lidar (light detection and ranging) that measures high-accuracy profiles of ozone while also providing aerosol and cloud data—was deployed in August 2016 to support a five-year investigation to study the impacts of African biomass burning. ESD is also making strides in developing new instruments for potential use on upcoming space missions. A Carbon Dioxide (CO_2) Sounder Lidar instrument employs a new type of laser system that will enable the collection of global carbon dioxide measurements around the clock—a capability that is not possible with existing space instruments.

NASA uses the vantage point of space to increase our understanding of our home planet, improve lives, and safeguard our future. The scientific discoveries enabled by NASA's Earth Science missions in FY 2016 have improved our understanding of our home planet.

NASA Researchers Improve Hazardous Weather Forecasts

Forecasters have known for years that anvil clouds indicate thunderstorms, but anvil tops can be miles wide, and it is sometimes difficult to distinguish where within those clouds hazardous weather may be occurring. NASA scientists and engineers are combining satellite images with novel algorithms to identify the most intense areas of these storms—areas where clouds extend above the flat top of the anvil. With this method, they can identify where severe winds, hail, or tornadoes

are most likely to occur within storm clouds. This information could help save lives in areas of the world, including the Plains and Midwest regions of the United States, where thunderstorms and tornados kill dozens of people every year. It can also be used by aircraft pilots wishing to avoid hazardous zones and insurance companies interested in identifying high-risk areas.

NASA Monitors Rainfall in U.S. Storms and Floods

When Tropical Depression Bonnie swept through the southern United States over Memorial Day weekend in 2016, it caused major flooding in Texas and Oklahoma, as well as soaking rains in South Carolina. Total rainfall estimates were made by NASA's Integrated Multi-satellitE Retrievals for GPM (IMERG), which relies on NASA and JAXA's Global Precipitation Measurement (GPM) satellite and other U.S. and international satellites. Estimates provided by IMERG help forecasters to better understand the extent of storms and can aid in recovery efforts and future predictions. IMERG estimates have been used to analyze storms throughout the United States, including most recently in Florida, Georgia, Louisiana, North Carolina, and New York.

NASA Observations Used to Track Groundwater in Pakistan

Farmers all over the world rely on irrigation systems to maintain their crops, but population booms and urbanization in recent decades have begun to deplete critical underground reservoirs in places like Pakistan. After receiving training, the Pakistan Council of Research in Water Resources began using data from NASA's Gravity Recovery and Climate Experiment (GRACE) mission in January 2016 to create monthly updates on groundwater storage changes in the Indus River basin. GRACE maps tiny variations in Earth's gravity, and since water has mass, it affects these measurements. This allows scientists in the United States and other countries to use GRACE data to monitor where water is and how it changes over time, providing estimates of the total amount of available water. Using satellites to gather these data can provide significant benefits in terms of cost and efficiency compared to ground-based monitoring.

New Seafloor Map Helps Scientists Find New Features

An international scientific team developed a new satellite-based map of the global ocean floor with unprecedented spatial detail and coverage. The map was constructed using data from the Jason-1 satellite, which was jointly developed by NASA and CNES, and ESA's CryoSat-2 satellite, as well as satellite missions flown in the 1980s and 1990s. These satellites provided data on Earth's gravity field as well as measurements of the height of the sea surface. Seafloor maps such as these are helpful to prospectors scouting for oil, gas, and mineral resources. They also help submariners and ship captains to navigate more safely, particularly in previously uncharted areas.

NASA Satellite Data Help Reduce Flights Sidelined by Volcanic Eruptions

Airborne ash particles from erupting volcanoes pose a significant danger to airline traffic. Suspected ash plumes often lead to flight cancellations and lengthy diversions. NASA researchers have improved the accuracy of volcanic ash forecasts by using satellite measurements of sulfur dioxide, a main component of volcanic emissions, coupled with satellite measurements of volcanic aerosols. The ash and sulfur dioxide observations are acquired by the Ozone Mapping Profiler Suite (OMPS) instrument flying on the joint NASA/NOAA/Department of Defense (DOD) Suomi National Polar-orbiting Partnership (Suomi NPP) satellite. Researchers are helping the worldwide network of Volcanic Ash Advisory Centers to routinely incorporate the satellite-based plume data into operational ash estimates and forecast products for commercial aviation.

Joint Agency Satellite Division

In addition to its own Earth observation satellites, NASA also develops and launches satellites on behalf of NOAA on a reimbursable basis through the Joint Agency Satellite Division (JASD). Descriptions of these satellite programs can be found in the Department of Commerce chapter of this report.

Heliophysics Division

We live in the extended atmosphere of a dynamic, active star. Our sun helps drive a continually changing magnetic and radiation system that surrounds it, Earth, and the planets—and also can affect astronauts and technology in space. It is the job of NASA's Heliophysics Division to study the nature of this star and its effects on the space environment, including the effects of space weather near Earth, which can impact radio communications systems, GPS accuracy, and power grids.

Heliophysics supports NASA's drive to explore: studying this complex system that connects the sun and the space environment helps us improve our ability to protect missions and astronauts from the hazards of space radiation. Additionally, heliophysics research provides insight into fundamental science throughout the universe. It can, for example, teach us more about the forces that forged the planets in our solar system and therefore help us better understand planetary evolution throughout the galaxy as we search for habitable planets.

Mapping out this interconnected system of sun and space requires a holistic study of the sun's connection to Earth and other planets at both small and large scales. To support this work, NASA's heliophysics missions seek to answer three key questions: What causes the sun to vary? How do Earth, the planets, and the heliosphere respond? What are the impacts on humanity?

An array of heliophysics missions provide key information to help solve these mysteries. NASA's Solar and Heliospheric Observatory (SOHO), with more than 20 years in space, and Solar Dynamics Observatory (SDO), which launched in 2010, continue to provide real-time images of the sun in multiple wavelengths, allowing scientists to examine trends in solar dynamics. Hinode, another sun-watching mission that provides nearly nonstop images of the sun, was developed in collaboration with JAXA and recently celebrated 10 years in orbit. Together with another NASA mission, the Solar and Terrestrial Relations Observatory (STEREO), these spacecraft allowed NASA to detect a solar flare from three different observatories simultaneously, providing the most comprehensive observations ever collected of a phenomenon called a current sheet: a very fast, very flat flow of electrically charged material that plays a crucial role in scientists' models of solar flares. NASA's Magnetospheric Multiscale (MMS) mission, which consists

of four identical spacecraft that orbit Earth, has been in space since 2014 and has provided important information on a phenomenon called magnetic reconnection, a fundamental process that initiates eruptions on the sun and produces auroras in the night sky. MMS studies magnetic reconnection in near-Earth space—the only place where we can study it up close—but what we learn from MMS in near-Earth space helps us understand the process throughout the universe, such as at other stars or the boundaries of black holes. It even plays a role in fusion energy research, as magnetic reconnection sometimes occurs in nuclear fusion chambers.

Findings based on observations from NASA's Van Allen Probes have revealed that the ring current—an electrical current carried by energetic ions that encircles our planet—behaves in a much different way than previously understood. The Interstellar Boundary Explorer (IBEX) mission provided new information about how our heliosphere, the magnetic bubble in which our sun and planets reside, interacts with interstellar space. Heliophysics uses high-altitude balloons for its research as well. Its Balloon Array for Radiation-belt Relativistic Electron Losses (BARREL) campaign, consisting of numerous research balloons, mapped for the first time how a solar storm caused Earth's magnetic field to shift and move.

A fleet of 17 solar, heliospheric, geospace, and planetary spacecraft operate simultaneously to help us understand the solar dynamics of the solar system. This fleet can be thought of as a single Heliophysics System Observatory. Experience has demonstrated that combinations of these missions enable larger-scale investigations that would not have been possible with one mission on its own. This distributed observatory has flexibility and capabilities that evolve with each new mission launched. Knowledge, data, and new interpretive models facilitate the path toward new scientific understanding.

New heliophysics missions currently being developed promise to further improve our understanding of the sun and its effects. Solar Probe Plus (SPP), scheduled for launch in 2018, is currently undergoing integration and testing. The spacecraft will get closer to the sun than any spacecraft has before, flying through the sun's outer atmosphere, or corona. The NASA and ESA Solar Orbiter collaboration mission will launch in 2018 and will provide better images of the regions around the sun's poles than have ever been captured before. Heliophysics is also embracing medium and small space missions that can provide important contributions to science. Both the Ionospheric Connection Explorer (ICON) and the Global-scale Observations

of Limb and Disk (GOLD) are scheduled to launch in 2017 to study Earth's thermosphere and ionosphere. GOLD will do so from geostationary orbit and as the first NASA science payload hosted on a commercial satellite. Another mission, the CubeSat to study Solar Particles (CuSP), will launch on NASA's Space Launch System (SLS) and be one of the first CubeSats to travel in interplanetary space.

The Heliophysics Division is sponsoring several technology projects that will lead to greater understanding of the sun and its interaction with Earth. For example, a new carbon composite heat shield has been developed to protect the SPP mission, which will need to withstand temperatures that reach nearly 2,500 degrees Fahrenheit—but keep the spacecraft's payload operating at room temperature. In addition, the CuSP mission will test the possibility of creating a cost-effective network of space science stations out of a number of similar small satellites.

The sun is most often thought of as a source of light and energy, but it affects Earth and space in so many more ways. Throughout our solar system, the space environment is dominated by activity on the sun. By providing insight into the fundamental dynamics and nature of the sun and its effects on our solar system, NASA's Heliophysics program improves our understanding of our star while providing important information for people as well as for systems on Earth and in space.

NASA Directly Observes Fundamental Process of Nature for First Time

NASA's MMS mission directly observed magnetic reconnection for the first time, providing a better understanding of a phenomenon that is one of the prime drivers of space radiation. The phenomenon can vary significantly, from an explosive reconnection that sends particles hurtling off at nearly the speed of light to a more slow and steady reconnection. New measurements made possible by MMS showed that magnetic reconnection is dominated by the physics of electrons. This new information can help to better protect spacecraft and astronauts as they travel farther from Earth.

Irregularities in Earth's Ionosphere Cause GPS Signals to "Twinkle" Like Stars

Scientists found that instabilities in the ionosphere peak twice—once at sunset and again in the middle of the night—rather than once, as previously believed. Further, they found that the second peak varies by season and is most pronounced from June through August. These irregularities cause radio signals, including those

used by the GPS system, to brighten and fade, reaching Earth at unpredictable times, degrading accuracy. Researchers still have many questions about the ionosphere and how it can affect GPS and other satellite systems, some of which they hope to answer with the upcoming ICON mission, scheduled to launch in 2017.

Images from Sun's Edge Reveal Origins of Solar Wind

NASA scientists used the Solar Terrestrial Relations Observatory to gather the first image of the edge of the sun to describe how the solar wind starts. Scientists found that the solar plasma shoots out from the sun as water does from a squirt gun, where water begins as a smoother and unified stream, but eventually breaks up into droplets, then smaller drops, and eventually into a fine, misty spray. In the case of solar plasma, scientists found that as one moves out from the center of the sun, the magnetic field strength drops faster than the pressure of the material, so the material begins to act more like a gas than like a magnetically structured plasma. The unique STEREO images captured the plasma in this early stage—equivalent to the disintegration of a steady stream of water into droplets.

NASA's THEMIS Sees Auroras Move to the Rhythm of Earth's Magnetic Field

Using data from NASA's Time History of Events and Macroscale Interactions during Substorms (THEMIS), a five-spacecraft mission dedicated to understanding the process behind auroras, scientists now have a better understanding of why auroras move the way they do. Scientists observed Earth's vibrating magnetic field in relation to the northern lights dancing in the night sky over Canada with both THEMIS and ground-based magnetic sensors and cameras, allowing them to directly link specific disturbances in Earth's magnetosphere with a magnetic response on the ground. They found that the aurora moved in harmony with the vibrating field line.

Solar Storms May Have Been Key to Life on Earth

A group of NASA researchers found that powerful solar explosions may have provided the crucial energy needed to warm Earth and turn simple molecules into the complex molecules, such as RNA and DNA, that are necessary for life. About four billion years ago, our sun shone with only about three-quarters the brightness

we see today and Earth received only about 70 percent of the energy from the sun that it does today, an amount that would have left the planet covered in ice. Using data from NASA's Kepler mission, scientists found that stars that resemble our sun the way it was a few million years after its birth have up to 10 daily "superflares"—enormous explosions so rare today that we experience them only once every 100 years or so. Particles from these solar events, together with Earth's weaker magnetic field at the time, provided the warmth needed to allow a liquid ocean and changed the atmosphere's chemistry in a way that made all the difference for life on Earth.

Planetary Science Division

NASA's Planetary Science Division (PSD) continues one of humanity's oldest scientific pursuits: the observation and discovery of our solar system's planetary objects. Planetary science uses flyby and orbiting spacecraft, landers, and rovers, and in some cases sample return. NASA advances understanding of our solar system from the innermost planet to the system's outer edges, providing insight into the makeup of planets, moons, comets, and asteroids. Planetary scientists seek to understand not only the characteristics of the solar system, but also how this system originated and evolved, whether life ever evolved elsewhere in our solar system, and what that knowledge can tell us about the origin of life on Earth.

NASA's Juno spacecraft entered orbit around Jupiter on July 4, 2016, after an almost five-year journey to the solar system's largest planet. Data collected by the spacecraft will provide insight into how Jupiter was born and how the entire solar system evolved. NASA's New Horizons mission, which flew by Pluto in 2015, continued to provide a wealth of discoveries in 2016. For example, scientists have found that Pluto may be home to ice volcanoes that were active in the recent geological past. After providing surprising evidence of a subsurface ocean on Saturn's moon Enceladus, the Cassini spacecraft made a series of close flybys of the moon in the beginning of FY 2016, sampling dust that evidence suggests originated from hydrothermal vents on the ocean floor. In October 2016, NASA's Mars Atmosphere and Volatile EvolutioN (MAVEN) mission completed one Mars year of science observations, providing new information about Mars's atmosphere and climate. In

September 2016, NASA launched the Origins, Spectral Interpretation, Resource Identification, Security–Regolith Explorer (OSIRIS-REx) spacecraft, which will travel two years to reach the near-Earth asteroid Bennu, collect a sample, and return it to Earth. The sample will be the largest returned from space since the Apollo era and will provide important insights into our understanding of the early solar system.

As these spacecraft continue their missions in space, others are being prepared for launch. NASA's Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) mission to study the deep interior of Mars is progressing toward a 2018 launch. It will be followed two years later by Mars 2020, a rover that will investigate a region of Mars where the ancient environment may have been favorable for microbial life and probe the Martian rocks for evidence of past life. Mars 2020 will also collect samples of soil and rock and store them on the surface for potential return to Earth by a future mission. NASA is formulating its flyby mission to Jupiter's moon Europa, which, with its ice-covered ocean containing more water than Earth, is widely considered one of the most promising places in the solar system for signs of present-day life.

Several technology developments funded by PSD achieved milestones this year that will enable future planetary and deep space missions. PSD-sponsored thermoelectric research resulted in the demonstration of advanced thermocouples for use in future Radioisotope Thermoelectric Generators that are twice as efficient as heritage devices. An innovative three-dimensional weaving technique is being used to develop a lightweight, yet robust, heat shield to protect future spacecraft against the extreme heat encountered upon entry into planetary atmospheres. Two newly designed neutron spectrometers will fly on board the CubeSat LunaH-Map to help map ice deposits near the Lunar South Pole, which may enable future missions to the moon.

NASA's Hubble Spots Possible Water Plumes Erupting on Europa

Astronomers used NASA's Hubble Space Telescope to capture images of what may be water vapor plumes erupting off the surface of Jupiter's moon Europa, bolstering previous Hubble observations that suggested the existence of such plumes. The plumes are estimated to rise about 125 miles (200 kilometers) before raining material

back down onto Europa's surface. If the plumes exist, it may be possible to sample Europa's ocean by flying through them, rather than drilling through miles of ice.

NASA Mission Reveals Speed of Solar Wind Stripping Martian Atmosphere

Mars once had a thick atmosphere warm enough to support liquid water, but this atmosphere has been gradually lost to space via stripping by the solar wind. Measurements from NASA's MAVEN mission showed that this loss increases significantly during solar storms. This suggests that the rate of atmospheric erosion may have been much higher billions of years ago, when the sun was younger and more active. Understanding how the planet transitioned from one that supports liquid water to one that does not is a key question for future deep space missions.

Curiosity Finds Evidence of Mars Crust Contributing to Atmosphere

NASA's Curiosity rover has found evidence that the surface material on Mars has contributed to the chemical makeup of its atmosphere over time, showing that processes of atmosphere loss are not the only dynamics at work in Mars's atmosphere. Scientists used Curiosity's Sample Analysis at Mars (SAM) instrument to carry out mass spectrometry on the surface of another planet for the first time. The measurements suggest that interaction with the surface changed the isotopic makeup of elements in the atmosphere, particularly xenon and krypton. Better understanding the interactions between the Martian atmosphere and crust provides scientists with greater understanding of planetary evolution.

NASA's Cassini Finds Monstrous Ice Cloud in Titan's South Polar Region

Scientists using data from NASA's Cassini spacecraft detected a large cloud of frozen compounds near the South Pole of Saturn's moon Titan. The ice cloud was detected as Titan transitioned from fall to winter, a season that will last about seven and a half years by Earth's calendar. By studying the size, altitude, and composition of the polar ice clouds, scientists can better understand the nature and severity of Titan's winter. The findings suggest that the onset of southern winter on Titan is much more severe than the late stages of winter in Titan's northern region, with temperatures in the South Pole reaching below –238 degrees Fahrenheit (–150 degrees Celsius).

Pluto's Widespread Water Ice

One of the surprising results of NASA's New Horizons mission to Pluto was the prevalence of water ice, which was considerably more widespread across Pluto's surface than expected. Water ice is Pluto's crustal "bedrock," with more volatile ices creating seasonally changing patterns on top of it. For example, in the informally named places called Sputnik Planum (the western region of Pluto's "heart") and Lowell Regio (far north on the encounter hemisphere), little or no water ice has been detected, suggesting it is well hidden beneath a thick blanket of other ices such as methane, nitrogen, and carbon monoxide.

Astrophysics Division

NASA's Astrophysics Division studies the universe—how the universe works, how it began, how it evolved, and whether there is life elsewhere in it. To understand these issues, astrophysics missions study the fundamental physics of our universe, including the nature of black holes, dark energy, dark matter, and gravity. The Astrophysics Division uses space observatories to examine the origin and evolution of galaxies, stars, and planets throughout the universe. Astrophysics also undertakes the search for life on planets around other stars, detecting exoplanets and determining whether they could harbor life. Astrophysics' driving questions are, how does the universe work; how did we get here; and are we alone?

NASA continues to operate three Great Observatories launched over the past 25 years: the Hubble Space Telescope, the Chandra X-ray Observatory, and the Spitzer Space Telescope. Other spacecraft, including the Fermi Gamma-ray Space Telescope, the Swift mission, and the Nuclear Spectroscopic Telescope Array (NuSTAR) mission, complement these large programs with more focused objectives. During its primary mission, the Kepler spacecraft detected thousands of exoplanet candidates, including ten Earth-like planets orbiting in the habitable zones of their host stars. Now in an extended phase of operations, Kepler is taking observations that will complement those to be made by future missions. The Astrophysics Division also operates the world's largest airborne observatory. The Stratospheric Observatory for Infrared Astronomy (SOFIA), a modified Boeing 747SP aircraft carrying a large reflecting telescope, can make observations that are impossible for even the largest and highest ground-based telescopes.

JWST, which is operated as its own program office within NASA's Science Mission Directorate, is undergoing integration and testing as it nears its 2018 launch date. Sometimes referred to as the follow-on to the Hubble Space Telescope, JWST will include a mirror that is more than double the diameter of the mirror on the Hubble Space Telescope, and it will collect data in infrared, rather than optical and ultraviolet, wavelengths. These characteristics will allow JWST to see more distant objects, gaze further back in time, and peer into dust clouds in which stars and planets are forming. JWST will use its infrared capabilities to study every phase in the history of our universe, from the creation of the first stars and galaxies, to the formation of solar systems capable of supporting life on planets like Earth, and even to the evolution of objects in our own solar system.

In 2016, NASA formally began work on the Wide Field Infrared Survey Telescope (WFIRST), which focuses on the nature of dark energy and dark matter and explores the evolution of the cosmos. WFIRST could also advance the search for worlds outside our solar system that could be suitable for life. WFIRST is scheduled to launch in the mid-2020s. In the meantime, NASA is developing smaller astrophysics missions: the Transiting Exoplanet Survey Satellite (TESS) and the Neutron star Interior Composition Explorer (NICER), both expected to launch in 2017. TESS will provide an all-sky survey to identify planets of all sizes orbiting the nearest and brightest stars. NICER will study the gravitational, electromagnetic, and nuclear-physics structure of neutron stars.

Several technologies developed by the Astrophysics Division made important contributions to advance scientific capabilities. A new type of thruster system designed to control a spacecraft's position to within a millionth of a millimeter was successfully deployed on board the Laser Interferometer Space Antenna (LISA) Pathfinder mission. NASA's Balloon Program Office completed the second test flight of its Super Pressure Balloon (SPB) in July, setting a new duration record for a mid-latitude flight of a large scientific research balloon. An instrument that employs newly developed absorber technology—the High-Resolution Airborne Wideband Camera-plus (HAWC+)—was installed on SOFIA. In conjunction with STMD, SMD is developing the WFIRST Coronagraph, the first high-contrast stellar coronagraph to be used in space. The WFIRST Coronagraph development effort progressed significantly in FY 2016, passing a key review and decision milestone.

NASA's Hubble Finds Universe Is Expanding Faster Than Expected

A team of scientists used NASA's Hubble Space Telescope to monitor the universe's current expansion rate with unprecedented accuracy. They discovered that the universe is expanding five to nine percent faster than expected based on the expansion rate predicted for the universe from its trajectory seen shortly after the Big Bang and on measurements made by NASA's Wilkinson Microwave Anisotropy Probe (WMAP) and the European Space Agency's Planck satellite missions. The finding may have important implications for improving our understanding of dark energy, dark matter, and dark radiation.

Hubble Makes First Atmospheric Study of Earth-Sized Exoplanets

Scientists used the Hubble Space Telescope to reveal clues about the chemical makeup of exoplanet atmospheres. They found that the two exoplanets they studied are unlikely to have the hydrogen-dominated atmospheres usually found on gaseous worlds, increasing the chances that these planets are habitable. Scientists hope to use Hubble to conduct follow-up observations to search for thinner atmospheres, composed of elements heavier than hydrogen, like those of Earth and Venus. Observations from future telescopes, including JWST, will help determine the full composition of these atmospheres. JWST also will analyze a planet's temperature and surface pressure—key factors in assessing its habitability.

NASA Telescopes Find Clues for How Giant Black Holes Formed So Quickly

Observations show that the supermassive black holes believed to be at the center of many galaxies formed very early—taking shape less than a billion years after the start of the universe in the Big Bang. Scientists used data from NASA's Great Observatories—the Chandra X-ray Observatory, the Hubble Space Telescope, and the Spitzer Space Telescope—to develop a theory to explain how young, supermassive black holes may have been formed. The new theory suggests that rather than forming from the creation and subsequent destruction of a massive star, which would take a longer period of time, these black holes formed directly when a cloud of gas collapsed, bypassing these intermediate phases. Scientists plan to use additional observations from future NASA observatories to further test this theory.

NASA's Spitzer Maps Climate Patterns on a Super-Earth

Using NASA's Spitzer Space Telescope, scientists were able to develop a temperature map of a super-Earth planet—a rocky planet nearly two times as big as ours—for the first time. The planet observed, 55 Cancri e, is tidally locked to its star, with one side of the planet always in daylight and the other always in the dark. Heat transport around the planet is inefficient, so the day side remains much hotter than the night side of the planet. Scientists have suggested that this means the planet does not have a thick atmosphere and winds. Instead, they have suggested that it may be home to lava flows that have become hardened on the night side and unable to transport heat. Additional observations, including those from the upcoming JWST, will help to confirm the findings.

Missing Water Mystery Solved in Comprehensive Survey of Exoplanets

Scientists combined data from NASA's Hubble and Spitzer Space Telescopes to study a series of hot, Jupiter-sized exoplanets that have been a challenge to observe due to their proximity to their stars. The combined observations allowed the scientists to work with a wider range of wavelengths and better understand why some of these planets seemed to have less water than expected—a long-standing mystery. Based on the data, they found that the clouds on the planets were likely masking detection of the water, ruling out the existence of dry, hot Jupiters.

Cross-Theme Activities

Answering the Nation's key science questions often requires significant technological innovation to develop instruments or platforms with capabilities beyond the current state of the art. SMD's targeted technology investments fill critical technology gaps, enabling NASA to build challenging and complex missions at an affordable cost such that groundbreaking science may be accomplished. The directorate works to ensure that NASA actively identifies and invests in the right technologies at the right time to address the Agency's science investigation needs. SMD technology development is part of a comprehensive Agency-wide strategy that involves extensive coordination with other Mission Directorates. This coordination helps ensure that crosscutting technology development needs are identified

across the Agency and that there is optimal return on investments to fulfill those needs. SMD accomplishes technology development through more than a dozen specialized technology programs that have been established in each of the four science research divisions.

During FY 2016, SMD also awarded 27 new cooperative agreements to enable SMD scientists and engineers to engage with learners of all ages. This restructured program allows for more streamlined and effective implementation of SMD content, leveraging past investments and partners across the United States. The program aims to effectively and efficiently link NASA science exploration of our home planet, the solar system, and the universe with learning environments. Each of the 27 awardees has an individual evaluation plan with independent evaluators to validate evidence-based performance against the needs identified at the outset of each effort. Additionally, SMD supported two significant White House events: the 2015 White House Astronomy Night and the White House Frontiers Conference.

Aeronautics Research Mission Directorate

In FY 2016, the Aeronautics Research Mission Directorate (ARMD) announced a ten-year plan for research that enables breakthroughs in the speed and efficiency of transport aircraft that are the backbone of the U.S. aviation system, as well as in realizing new markets for smaller aircraft—from unmanned aircraft systems (UASes) to the potential for new modes of personal transport—and in automation tools that improve efficiency while maintaining safety in our Nation's airspace system.

The centerpiece of the plan is New Aviation Horizons—an initiative to design, build, and fly a series of flight demonstration vehicles, or "X-planes." If fully successful, the X-planes will test advanced technologies that can, in the same aircraft, reduce fuel use by 50 percent, emissions by 75 percent, and noise to nearly one-eighth of today's levels without compromising payload capacity, speed, or range. If such technologies find their way into a U.S. airline's fleet, ARMD computer models show that the economic impact could be $255 billion in operational savings over 25 years.

More information about the full 10-year plan, including New Aviation Horizons, is available online at *http://www.aeronautics.nasa.gov/pdf/NASA-Aero-10-Yr-Plan-508.pdf*.

During FY 2016, NASA also completed a series of long-term research roadmaps to enable major outcomes in six strategic thrust areas identified in its strategic vision for aeronautics research. The roadmaps were developed in partnership with the aviation community and reflect visionary solutions to aviation system needs that will ensure major benefits in mobility, environmental sustainability, and safety while ensuring continued long-term aviation technology leadership in this rapidly expanding global industry. More information is available online at *http://www.nasa.gov/aeroresearch/strategy*.

Advanced Air Vehicles Program

NASA achieved a major milestone in enabling the development of low-noise commercial supersonic aircraft when the Advanced Air Vehicles Program (AAVP) completed the Low Noise Propulsion for Low-Boom Aircraft technical challenge. This technical challenge addressed the development of computer-based design tools and innovative concepts for integrated low-noise supersonic propulsion systems and demonstrated these concepts through ground testing. The research recognized that future commercial supersonic aircraft would have to be as quiet as possible to meet the same stringent airport noise regulations that govern the subsonic fleet.

NASA announced the selection of a team led by Lockheed Martin Aeronautics Company of Palmdale, California, to complete a preliminary design for a low-boom supersonic flight demonstration aircraft by June 2017. The selection advanced NASA's work to enable the aviation industry's decision to open supersonic travel, especially over land, to the flying public. The Lockheed Martin team includes subcontractors GE Aviation of Cincinnati and Tri Models, Inc., of Huntington Beach, California. The design and supporting documentation will be used by NASA to prepare for the detailed design, building, and testing of a low-boom supersonic X-plane. More information is available online at *http://www.nasa.gov/press-release/nasa-begins-work-to-build-a-quieter-supersonic-passenger-jet*.

A unique technique for capturing images of shock waves created by supersonic aircraft was used in the air and from the ground. The schlieren technique yielded striking images of shock waves from a T-38 that provide data to further validate advanced solutions for reducing the levels of sonic booms. More information is available online at *http://www.nasa.gov/centers/armstrong/features/bosco.html*.

NASA advanced the technical readiness of the most promising advanced configurations for future subsonic transports. The performance and design of a Truss Braced Wing (TBW) aircraft conceptual design, which is a viable technology to reduce transport aircraft fuel use, was tested using a high-fidelity aerodynamic wind tunnel model in the 11- by 11-Foot Transonic Wind Tunnel at NASA's Ames Research Center. More information is available online at *http://www.nasa.gov/image-feature/ames/slimmed-down-aircraft-wing-expected-to-reduce-fuel-and-emissions-by-50*.

In FY 2016, NASA also awarded six-month contracts to four companies to define the technical approach, schedule, and cost for one or more large-scale, ultra-efficient subsonic X-plane concepts. The companies were Aurora Flight Sciences Corporation, a small business located in Manassas, Virginia; Dzyne Technologies, a small business located in Fairfax, Virginia; Lockheed Martin Aeronautics Company of Fort Worth, Texas; and the Boeing Company of Hazelwood, Missouri. More information is online at *http://www.nasa.gov/aero/nasa-green-aviation-x-planes*.

NASA selected progressive damage analysis (PDA) technologies for further development in the second phase of the Advanced Composites Project. By comparing blind predictions with experimental results, NASA completed the characterization of PDA methods, nondestructive inspection technology, and manufacturing process models for composites (current capability and technology gaps). When complete, these PDA models will provide damage-progression methods that more accurately represent the failure mechanics for the composite structural component and applied loading.

In partnership with other Government agencies and industry, NASA demonstrated a new type of engine power turbine that will advance the efficiency of propulsion systems for future vertical lift vehicles. The Variable-Speed Power Turbine (VSPT) component tests will demonstrate the ability to operate the power turbine efficiently over a wide operating-speed range of the engine. The VSPT concept will result in engines and vehicles with higher performance and greater fuel efficiency.

NASA performed disciplined technical exploration of new, revolutionary hybrid-electric propulsion concepts. Design and fabrication were completed and relevant testing was initiated on a 750-kilowatt fully superconducting electrical machine with a new power-efficient stator design. Concurrently, engineers completed a conceptual design for a hybrid gas-electric propulsion system concept for a Boeing 737–class aircraft that could achieve all of the intended vehicle-level benefits in reduced energy consumption, noise, and emissions. A new electric motor test stand began operations at NASA's Armstrong Flight Research Center. More information is available online at *http://www.nasa.gov/feature/it-s-electric-nasa-glenn-engineers-test-next-revolution-aircraft* and *http://www.nasa.gov/centers/armstrong/features/electric_motor_test_stand.html*.

Airspace Operations and Safety Program

NASA continued to make significant progress in developing automation that enables the success of the Nation's Next Generation Air Transportation System (NextGen) initiative in partnership with the FAA and industry.

Development of an integrated set of NextGen tools and technologies, known as Interval Management—Terminal Area Precision Scheduling and Spacing Technologies or Air Traffic Management Technology Demonstration–1 (ATD-1), continued as preparation for an FY 2017 flight demonstration. The ATD-1 tools will provide an efficient arrival solution for managing aircraft beginning from just prior to top-of-descent and continuing down to the runway, which can improve airport throughput and reduce delays, fuel use, noise, and emissions at busy airports. FY 2016 preparations included the development of simulation tools for pilot preparation. More information is available online at *http://www.nasa.gov/aero/nasa-aircraft-arrival-technology-gets-big-test-in-2017*.

In FY 2016, progress also was made with ATD-2, an initiative that provides coordinated aircraft surface movement schedules to air traffic managers working the airport ramp, control tower, terminal area, and air route centers. NASA is working with the FAA, airlines, aircraft and avionics manufacturers, ground-based automation system integrators, and airports to prepare to test this integrated set of technologies at a dense terminal of a busy commercial airport by 2017. To

that end, an aeronautical research laboratory was opened in June 2016 at the Charlotte Douglas International Airport (North Carolina). An initial engineering shadow evaluation of ATD-2 surface management tools was conducted, and two Phase 1 Engineering Shadow Evaluations were completed at the lab late in FY 2016. More information is available online at *http://www.nasa.gov/press-release/transportation-department-nasa-partners-visit-charlotte-to-open-test-lab-to-streamline*.

In FY 2016, NASA also helped deliver and train personnel on an air traffic management tool at American Airlines' Integrated Operations Center in Fort Worth, Texas. The National Airspace System Constraint Evaluation and Notification Tool (NASCENT) enables airline flight coordinators to call out adjustments in a flight's trajectory in real time, particularly to avoid bad weather. At the heart of the technology is NASA-developed software called Dynamic Weather Routes. More information is available online at *https://www.aviationsystems.arc.nasa.gov/research/strategic/dwr.shtml*.

A demonstration of technologies that could be part of a system to safely manage the operations of small unmanned aircraft systems (UASes), or "drones," was completed in FY 2016. The Technology Capability Level (TCL) 1 demonstration took place first at a single site and, then, later in a national campaign involving six geographically diverse FAA UAS test sites. NASA, the FAA, and industry partners participating in eight different states simultaneously flew 22 drones to assess rural operations of the NASA UAS Traffic Management (UTM) research platform. More information is available online at *http://www.nasa.gov/feature/ames/nasa-marks-success-for-most-complex-drone-traffic-management-test-yet-at-faa-test-sites*.

Another goal realized for FY 2016 was delivery of NASA's contribution to a set of UAS Minimum Operating Performance Standards (MOPS) data, analysis, and recommendations to the RTCA Special Committee-228 on MOPS for UASes. Based on a series of flight test and other activities, this first series of MOPS addresses standards for detect-and-avoid as well as command and control solutions for UASes operating in a specific segment of airspace.

With regard to aviation safety, two studies were completed that identified safety metrics to be used in developing a roadmap for achieving safety assurance in real time throughout the National Airspace System. Completing the studies is the next step in developing technologies that can monitor aircraft and system health in real

time, assess any risks, alert the crew to risks, and then mitigate those risks. This type of work represents a "next generation" approach to keeping aviation safe by introducing more predictive tools.

NASA's pioneering Aviation Safety Reporting System (ASRS) marked its 40th anniversary during FY 2016. Established under a Memorandum of Understanding between NASA and the FAA, the system collects, analyzes, and responds to voluntarily submitted aviation safety incident reports to reduce aviation accidents and improve safety. The confidential reports are also used to identify deficiencies and discrepancies in the National Airspace System that need to be remedied. More information is available online at *http://www.nasa.gov/home/hqnews/2006/nov/HQ_06345_ASRS_turns_30.html*.

In FY 2016, an important tool for air traffic researchers called the Sherlock Air Traffic Management Data Warehouse came online at NASA's Ames Research Center. For the first time, air traffic researchers were now able to view and analyze archived flight data collected and merged from all air traffic facilities across the United States, with fast update rates ranging from one second to 12 seconds for every flight's position. Sherlock merges all of the air traffic facility data to produce analysis-ready, end-to-end flight information at these improved resolutions for the entire U.S. airspace. More information is available online at *http://www.nasa.gov/feature/ames/nasa-pulls-together-national-data-to-sleuth-out-air-traffic-improvement-mysteries*.

Integrated Airspace Systems Program

FY 2016 brought the official end to this program's Environmentally Responsible Aviation (ERA) project. Created in 2009 and completed in 2015, ERA's mission was to explore and document the feasibility, benefits, and technical risk of inventive vehicle concepts and enabling technologies that would reduce aviation's impact on the environment. Project researchers focused on eight major integrated technology demonstrations falling into three categories: airframe technology, propulsion technology, and vehicle systems integration. Results from ERA's demonstrations led directly to NASA's ability to formulate and propose the New Aviation Horizons X-planes initiative. The purpose of the X-planes is to take the ERA advanced technologies to flight, where they can best

prove their potential to dramatically reduce aircraft noise, fuel use, and emissions. More information is available online at *http://www.nasa.gov/press-release/nasa-research-could-save-commercial-airlines-billions-in-new-era-of-aviation*.

Technologies that could be part of a system for allowing larger UAS to routinely fly in the National Airspace System were tested during FY 2016. Flight Test Series 4 (FT4) took place at NASA's Armstrong Flight Research Center in California and consisted of 19 flights over a nine-week period. The flights tested detect-and-avoid algorithms developed by NASA; General Atomics Aeronautical Systems, Inc.; Honeywell; and other industry partners that, for the first time, could validate MOPS, established by RTCA Special Committee 228. To test these algorithms, over 260 scripted encounters were performed between the Ikhana and piloted "intruder" aircraft. The algorithms successfully generated precise alerts necessary for the pilot controlling the Ikhana from the ground to remain well clear and avoid collisions. More information is available online at *http://www.nasa.gov/feature/two-month-uas-flight-test-series-concludes*.

Transformative Aeronautics Concepts Program

In FY 2016, a general aviation–sized aircraft destined to be a build-and-learn test bed for all-electric propulsion received the first X-plane designation from the U.S. Air Force to NASA in a decade. The X-57 experimental airplane was named "Maxwell" in honor of James Clerk Maxwell, the 19th-century Scottish physicist who did groundbreaking work in electromagnetism. During the next few years, the X-57's original wing and two gas-fueled piston engines will be replaced with a long, skinny wing embedded with 14 electric motors: 12 on the leading edge for takeoffs and landings, and one larger motor on each wingtip for use while at cruise altitude. More information is available online at *http://www.nasa.gov/press-release/nasa-electric-research-plane-gets-x-number-new-name*.

The fuselage of the X-57 aircraft, a Tecnam P2006T, arrived in California later in FY 2016, where work began to convert all of the vehicle's systems to electric power, including the two engines, and to ready it for the later installation of a high-lift experimental wing. More information is available online at *http://www.nasa.gov/centers/armstrong/features/X-57_fuselage_arrives.html*.

The state of the art in aeronautics modeling and simulation capability was advanced in FY 2016 with the development of improved physics-based tools and methods. These types of tools are vital to the ability to realize the non-traditional aircraft and propulsion systems of the future. One example is a first-of-its-kind simulation of sound produced by air through the blades of an open-rotor propulsion system. NASA verified the simulation accuracy and compared sound pressure level ranges with extensive wind tunnel test data. More information is available online at *http://www.nasa.gov/image-feature/ames/nasa-supercomputer-simulations-help-improve-aircraft-propulsion-design*.

To achieve the goal of better engines on future aircraft, materials engineers at NASA's Glenn Research Center in FY 2016 investigated promising advances in high-temperature materials that can be used to make turbine engine components. These materials, called ceramic-matrix composites (CMCs), are lighter and stronger than conventional materials and can withstand the demanding forces of the extremely high temperatures generated in the core of jet engines. More information is available online at *http://www.nasa.gov/feature/ceramic-composites-revolutionize-engine-efficiency*.

In FY 2016, NASA began the second year for a number of cross-Center, multidisciplinary research activities that identify whether certain transformative ideas are feasible; i.e., can a high-voltage, lightweight, efficient power-distribution system enable hybrid electric aircraft propulsion systems? A new set of five activities was announced, including alternative fuel cells and new mechanisms for changing the shape of an aircraft wing in flight. More information is available online at *http://www.nasa.gov/press-release/nasa-charges-toward-greener-aviation-with-novel-concepts*.

NASA also debuted the University Leadership Initiative (ULI), which uses the NASA Research Announcement process to competitively award university-led teams that develop solutions for technical challenges associated with NASA's six aeronautics research areas. More information is available online at *http://www.nasa.gov/aero/nasa-debuts-universities-initiative*.

Space Technology Mission Directorate

In FY 2016, the Space Technology Mission Directorate (STMD) made significant progress toward advancing space technology for NASA, other Government agencies, and the commercial space industry. Investments focused primarily on seven key thrust areas: 1) in-space propulsion; 2) high-bandwidth space communications; 3) advanced life support and resource utilization; 4) entry, descent, and landing (EDL) systems; 5) space robotic systems; and 6) lightweight space structures.

STMD manages nine major technology development programs performed at each of NASA's ten Centers, as well as activities such as technology transfer, regional economic development, and NASA Solve—the Agency's initiative for public engagement in crowdsourced challenges and prize competitions. STMD plays a key role in NASA's contribution to the Nation's innovation economy through involvement in several national initiatives, including the Advanced Manufacturing Partnership and the National Robotics Initiative.

In FY 2016, STMD evaluated over 2,400 proposals and funded over 700 new selections for awards, investing over $225 million. Below are a few of the notable achievements in FY 2016.

Technology Demonstration Missions

Solar Electric Propulsion

NASA's Solar Electric Propulsion (SEP) project is developing critical technologies to enable cost-effective access to inner solar system destinations such as Mars. SEP technology can also support more affordable missions for commercial and Government operations in Earth orbit and cislunar space. Work has continued at NASA's Glenn Research Center on a 12.5-kilowatt Hall Effect thruster and power-processing units. A test unit operated in a vacuum chamber across its whole performance range and successfully ran for over 1,700 hours. This electric thruster employs magnetic shielding that enables it to operate continuously for years, a capability needed for deep space exploration missions. In FY 2016, a commercial vendor, Aerojet Rocketdyne, was selected for a three-year contract to develop a propulsion system engineering unit and to deliver four flight units to be employed

in an upcoming flight demonstration mission. Also, large, high-power solar array concepts previously developed by ATK and Deployable Space Systems through STMD solicitations have been incorporated into commercial spacecraft designs.

Green Propellant Infusion Mission

NASA's Green Propellant Infusion Mission (GPIM) made significant progress toward launching a spacecraft designed to test the unique attributes of a high-performance, nontoxic, "green" fuel on orbit next year. The propellant, a hydroxyl ammonium nitrate–based fuel/oxidizer mix also known as AF-M315E, may replace the highly toxic hydrazine and complex bipropellant systems in use today, providing enhanced performance and volumetric efficiency. GPIM prime contractor Ball Aerospace & Technologies Corp. successfully integrated the propulsion subsystem—built by Aerojet Rocketdyne in Redmond, Washington—into the Ball Configurable Platform 100 small-satellite spacecraft as the primary payload. System performance and environmental testing of the GPIM integrated space vehicle successfully concluded in January. As of the end of FY 2016, the GPIM spacecraft had completed all required testing and was currently in storage, awaiting mission call-up. Launch to low-Earth orbit in late 2017 was planned in partnership with the U.S. Air Force's Space Test Program (STP)-2 mission aboard a SpaceX Falcon 9 Heavy booster.

Deep Space Atomic Clock

The Deep Space Atomic Clock (DSAC) project is designed to fly and validate a miniaturized, ultra-precise, mercury-ion atomic clock that is orders of magnitude more stable than today's best navigation clocks, forever changing the way we conduct deep space navigation. The clock should provide enhanced navigation accuracy, increased science data bandwidth, and improved gravitational measurements necessary for future planetary science and exploration missions. In late 2017, following testing aboard the host spacecraft provided by Surrey Satellite Technology U.S. of Englewood, Colorado, the plan is for the DSAC payload to be lofted to orbit as part of the U.S. Air Force's Space Test Program (STP)-2 mission aboard a SpaceX Falcon 9 Heavy booster.

Laser Communication Relay Demonstration

The Laser Communication Relay Demonstration (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 and using significantly less mass and power. The LCRD project continued to meet developmental milestones on its way to a flight test in 2019 to demonstrate bidirectional optical communications from geosynchronous orbit, providing significantly higher data rates using comparable mass and power. In FY 2016, the project completed a replan to baseline the payload to fly on the U.S. Air Force Space and Missile Systems Center's Space Test Program–3.

Restore-L

The Restore-L mission seeks to demonstrate satellite-servicing technologies. The Restore-L project began in STMD in mid–FY 2016. The project will be restructured to reduce its cost and better position it to support a nascent commercial satellite servicing industry.

In-Space Robotic Manufacturing and Assembly

NASA selected three companies for Technology Demonstration Mission Phase 1 ground-based projects:

- Orbital ATK (Dulles, Virginia), for the project entitled Public-Private Partnership for Robotic In-Space Manufacturing and Assembly of Spacecraft and Space Structures," which will perform an integrated ground demonstration including a robotically deployed rigid backbone and an upgraded Tendon-Actuated Lightweight In-Space MANipulator (TALISMAN) system.
- Space Systems Loral (Palo Alto, California), for the project entitled "Dragonfly: On-Orbit Robotic Installation and Reconfiguration of Large Solid RF Reflectors," which will modify existing robotic antenna equipment to perform a high-fidelity antenna assembly ground demonstration to provide next-generation performance advancements in geostationary communications satellites (comsats).

- Made in Space, Inc. (Moffett Field, California), for the project entitled "Versatile In-Space Robotic Precision Manufacturing and Assembly System," which will utilize the company's Archinaut technology platform for in-space additive manufacturing and assembly in a space environment test.

Evolvable Cryogenics

In FY 2016, the eCryo team held an industry workshop to disseminate recent data and analysis results. The Integrated Vehicle Fluids (IVF) system, developed by United Launch Alliance, which will be used to capture vented gaseous propellant as a secondary power source, completed two phases of testing, and advanced from Phase B to Phase C. The Structural Heat Intercept Insulation Vibration Evaluation Rig (SHIIVER) test system design continues. Engineers and technicians continued work on the Radio Frequency Mass Gauge (RFMG) in preparation for a planned flight demonstration in the first quarter of FY 2017.

Game Changing Development

Phase Change Material Heat Exchanger

In FY 2016, the Game Changing Development (GCD) Program successfully developed and launched a self-contained, wax-based heat exchanger to the International Space Station (ISS). Typically, crewed spacecraft use radiators to reject heat, but traditional radiators are not sized to handle the maximum amount of heat rejection, such as during launch, reentry, and planetary orbits. During these times, a supplemental heat rejection device—such as an evaporator—is used to maintain the spacecraft's full heat rejection requirement. This new, wax-based heat exchanger is self-contained and could help offset heat and better regulate temperatures experienced by spacecraft like Orion. The Phase Change Material Heat Exchanger (PCM HX) launched on the SpaceX CRS-9 flight on July 18, 2016, and on-orbit testing began. The goal is to provide a report on this flight-proven PCM HX to stakeholders, like the Orion spacecraft team, in order for it to be considered for use on Exploration Mission–2, slated to be the NASA Space Launch System's first crewed mission.

Extreme Environment for Solar Power

In FY 2016, GCD selected proposals from NASA's Jet Propulsion Laboratory in Pasadena, California; the Boeing Company of Huntington Beach, California; the Johns Hopkins Applied Physics Laboratory of Laurel, Maryland; and ATK Space Systems of Goleta, California, which were submitted in response to the Extreme Environment for Solar Power solicitation. The Extreme Environment for Solar Power project aims to develop a new generation of solar-power technologies that operate in high-radiation and low-temperature environments to improve mission performance, increase solar array life, and enable solar-powered vehicles to explore deeper into space than ever before. Initial contract awards are for as much as $400,000, providing awardees with funding for nine months of system design, component testing, and analysis. This effort has been conducted in collaboration with the Planetary Science Division within NASA's Science Mission Directorate (SMD)—our primary end users. Enhanced low-intensity, low-temperature (LILT) solar power will allow NASA to go deeper into the solar system without the complexity and costs associated with nuclear-based solutions.

High-Performance Spaceflight Computing

In FY 2016, GCD released a Request for Proposal (RFP) entitled "High Performance Spaceflight Computing (HPSC) Processor Chiplet." The HPSC project is a joint STMD, SMD, and U.S. Air Force Research Laboratory activity. Its goal is to develop a next-generation, radiation-hardened, general-purpose, multicore processor to meet on-board computing needs of future crewed spacecraft and robotic technologies. The Development Phase of the HPSC project should consist of a preliminary design phase culminating in a Preliminary Design Review (PDR), a detailed design phase culminating in a Critical Design Review (CDR), a fabrication phase, and a test and characterization phase, all over a total of four years.

NICER/SEXTANT

In the summer of 2016, GCD successfully delivered the Station Explorer for X-ray Timing and Navigation Technology (SEXTANT) to NASA's Kennedy Space Center in preparation for its demonstration with the Neutron star Interior Composition Explorer (NICER) hardware aboard the ISS in FY 2017. In

collaboration with SMD, GCD selected the project in 2013 as an Explorer Mission of Opportunity. The goal of the NICER/SEXTANT mission will be to investigate pulsars and demonstrate real-time, autonomous spacecraft navigation using pulsars as beacons.

Small Business Innovative Research and Small Business Technology Transfer

NASA awarded 561 proposals for a total of $172.5 million in FY 2016. Specifically, NASA selected 341 Small Business Innovative Research (SBIR) and 58 Small Business Technology Transfer (STTR) Phase I proposals for award to 257 U.S. small businesses to establish the scientific, technical, and commercial feasibility of each proposed innovation. In addition, NASA made 138 SBIR, three SBIR Select, and 21 STTR Phase II awards to further expand upon their Phase I work. Furthermore, the Commercialization Readiness Program (CRP) provided FY 2016 funds in the amount of $5.5 million to 14 CRP contracts awarded in FY 2014 and FY 2015. Additionally, 24 Phase II Extended/Expanded options were exercised for $5.5 million, and 30 Phase III awards were made leveraging $10.6 million in non-SBIR/STTR funding. In FY 2016, the program published an economic impact report on the NASA SBIR/STTR program, which indicated a $2.69 return for every dollar spent on awards. A few highlights from FY 2016 awardees include the following:

- Tethers Unlimited received a Phase II award for its Positrusion Filament Recycling System for the ISS (a system for recycling additive manufacturing [3D printing] filament). Tethers will show the flexibility of producing replacement parts, thus reducing mass and increasing the probability of mission success. This technology is scheduled to be demonstrated aboard the ISS in early 2018.
- Intelligent Automation, Inc., of Rockville, Maryland, won awards for Phases I through III for the MetroSim technology, which allows airport planners, traffic flow management experts, airline dispatchers, air traffic controllers, and pilots to increase efficiency and certainty in operations planning and recover quickly from disruptive events and weather conditions.

For additional SBIR/STTR success stories, visit the SBIR/STTR Web site at *http://sbir.nasa.gov/success-stories*.

Small Spacecraft Technology Program

The program accomplished several flight demonstration missions and completed final preparations for several others in FY 2016. The Optical Communications and Sensor Demonstration (OCSD) project launched its engineering development unit on October 8, 2015, as a precursor mission and successfully operated several new systems, including a miniature star tracker and radio. Operations of the satellite have continued throughout the year as the team prepares for the primary mission to demonstrate laser communications with two identical satellites to be launched in early 2017. The Nodes satellites, another Small Spacecraft Technology Program (SSTP) project, were launched to the ISS in December 2015 and deployed into orbit in May 2016. Nodes accomplished all of its mission objectives to demonstrate the operation of a swarm of low-cost science satellites during the first few weeks of flight. The satellites were then turned over to Santa Clara University, which will operate them for the remainder of their orbital life. In November 2015, the Maraia Earth Return Capsule launched on a suborbital rocket for a supersonic reentry test flight, using a new deployment device for small spacecraft research missions. Initially lost after a reentry anomaly, the capsule was recently found largely intact, and any recoverable flight test data will inform future small reentry vehicle experiments.

Three important technology demonstration missions completed Flight Readiness Reviews in 2016 and are now awaiting launch in 2017. The three missions are the Integrated Solar Array and Reflectarray Antenna (ISARA) for advanced communications, the CubeSat Proximity Operations Demonstrator that will attempt autonomous rendezvous and docking, and the OCSD mission described above.

The program issued an RFP for a small satellite bus for the Pathfinder Technology Demonstrator series. The Pathfinder vendor (Tyvak) was announced in January 2017. Four "tipping point" projects are now under way for the development and demonstration of new propulsion and control systems, as well as several advanced propulsion projects funded in partnership with the SBIR program. STMD defines a technology as being at a "tipping point" if an investment in a demonstration of its

capabilities will result in a significant advancement of the technology's maturation, a higher likelihood of infusion into a commercial space application, and a significant improvement in the partner's ability to successfully bring the technology to market. Eight university-NASA collaboration projects for small spacecraft technology were initiated in 2016 and will continue into a second year, while eight new projects were selected for 2017–18. These projects involve 16 universities working with researchers from almost all of the NASA Centers.

Flight Opportunities

The Flight Opportunities program flew 36 payload flights in FY 2016 for 32 different space technologies. The program supported Entry, Descent, and Landing technology demonstrations from NASA's Jet Propulsion Laboratory and Carnegie Mellon University, as well as Mars landing technologies such as Terrain Relative Navigation and Guidance for Fuel Optimal Large Diverts (G-FOLD) on Masten Space Systems vehicles.

Space Technology Research Grants

The Space Technology Research Grants program has funded research at 98 universities across 42 states, with a total of 438 grants since its inception. In FY 2016, the program made 15 Early Stage Innovations awards, 58 NASA Space Technology Research Fellowship awards, and eight Early Career Faculty awards. Some highlights from FY 2016 include the following:

- Researcher Heather Hava from the University of Colorado Boulder received the prestigious "Eat it!" Lemelson-MIT Student Prize for inventing a smart chamber to autonomously grow plants in a space habitat.
- Researcher Scott Zavada from the University of Michigan demonstrated the use of in situ polymerizable liquid as an autonomic healing layer for rigid structures such as lunar and Martian habitats.
- Researcher Manijeh Razeghi has developed a mid-infrared electrically tunable quantum-cascade laser (QCL) that can be used in spectroscopy for atmospheric chemistry.

- Lucas Hartsough, a researcher from Rice University, quantitatively described gene expression output as a function of time-varying inputs of light, thereby advancing both synthetic biology and optogenetics; his research was the basis of a Center Innovation Fund award.

NASA Innovative Advanced Concepts

NASA Innovative Advanced Concepts (NIAC) made 13 Phase I and eight Phase II awards across industry, academia, and NASA Centers, while completing 15 2015 Phase I studies and five 2014 Phase II studies. One example of a NIAC success story in FY 2016 was the Directed Energy Propulsion for Interstellar Exploration study, which inspired an external foundation to devote $100 million toward its proposed method of sending probes to another star system.

Centennial Challenges

The Centennial Challenges program conducted four competition events in FY 2016 and awarded prize money in each of the competitions for a total prize purse of $980,000. The program also opened two new challenges for a total of six active challenges in FY 2016. For the fifth and final year of the Sample Return Robot (SRR) Challenge, 18 teams competed in Level 1 (L1); five qualified for Level 2 (L2), and each of those five won $5,000. Seven teams competed in L2, and West Virginia University won the $750,000 award. Eighteen teams competed in the second year of the Mars Ascent Vehicle (MAV) Challenge, wherein teams were challenged to develop a robotic system that could load a sample into a rocket, launch to a predetermined altitude, and safely return the sample container to Earth. Cornell University won first place, Madison West High School in Wisconsin won second, and Tarleton State University in Texas won third. The second Ground Tournament of the Cube Quest Challenge was conducted in March 2016; of the 10 participating teams, five teams won $30,000 each. The purpose of the challenge is to design, build, and launch flight-qualified, small satellites capable of advanced operations near and beyond the moon. Three CubeSats from this challenge will be launched on NASA's Exploration Mission–1 as secondary payloads. The Space

Robotics Challenge and Vascular Tissue Challenge were also initiated in FY 2016. Space Robotics seeks to advance autonomous perception and manipulation software for the Robonaut-5 humanoid robot. The Vascular Tissue Challenge goal is to advance the field of tissue engineering by successfully growing thick, vascularized human tissue from a major organ.

Technology Transfer

NASA's Technology Transfer program continued to share the Agency's technology with industry, academia, and other Government agencies at an unprecedented rate, making it simpler and faster for end users to access the benefits of NASA's investments in aerospace research. NASA's patent licensing increased nearly 400 percent over its FY 2011 level, and its software release has more than doubled. In FY 2016, the program completed 94 patent licenses and 12 copyright licenses. New initiatives included "Startup NASA," which provides favorable terms and assistance to new enterprises forming to commercialize NASA technology, and the "Gift to the Public Domain," which dedicated several dozen patents for unencumbered public use.

Regional Economic Development

NASA's Regional Economic Development (RED) program brings NASA technology and expertise to targeted regions across the country to drive technology commercialization and to develop capabilities for stronger regional economies. To support these goals, RED held six major commercial partnership events in FY 2016, with a focus on small and mid-sized businesses: TechConnect in Dayton, Ohio; Technology Docking on the Space Coast in Florida; the IDEAHub Regional Innovation Symposium in southern California; the Industry Technology Capabilities Summit in Philadelphia, Pennsylvania; Technology Days and Hampton Roads Unmanned Systems Opportunity Exchange in Hampton Roads, Virginia; and Adopt-A-City III as part of the White House Strong Cities, Strong Communities Program in Cleveland, Ohio.

NASA Historically Black Colleges and Universities and Minority Serving Institutions Technology Infusion Road Tour

With the assistance of Large Prime Contractors and small businesses, NASA continues to enhance its industrial base with Historically Black Colleges and Universities (HBCUs) and Minority Serving Institutions (MSIs) through various outreach events tailored to university faculty members and students. In FY 2016, STMD, in a collaborative effort with the Office of Small Business Programs (OSBP) and the Office of Education, developed a new initiative to engage more HBCUs and MSIs in the Agency's industrial base: the NASA HBCU/MSI Technology Infusion Road Tour. These institutions are given a platform to learn about upcoming technology topics and how to respond to SBIR/STTR solicitations. Past and present SBIR/STTR awardees highlight their success stories and the opportunities participating in the program has afforded them.

As the only Federal agency with a one percent goal for supporting HBCUs/MSIs, NASA seeks new initiatives to engage interested universities/institutions in supporting our mission. The NASA HBCU/MSI Technology Infusion Road Tour was also designed to assist NASA and Large Prime Contractors in meeting or exceeding the mandated HBCU/MSI goal.

Department of Defense

DOD

Aeronautics Activities

Fixed-Wing Aircraft

Over the course of FY 2016, the KC-46A Pegasus program completed the first flights of the final three test aircraft. These flights opened the door to complete (in July 2016) the required flight testing for the August 2016 Milestone C production decision. The program received Milestone C approval on August 12, 2016, from the Under Secretary of Defense for Acquisition, Technology, and Logistics and awarded the contract option for the production of Lots 1 and 2, totaling 19 KC-46A aircraft, to Boeing. Flight testing continues as the team works toward supplying the aircraft to the warfighter.

In January 2016, the Air Force awarded the first contract for the Presidential Aircraft Recapitalization (PAR) program. The initial award was for program risk-reduction activities as the first step in a deliberate process to control program risks and reduce life-cycle costs. Additionally, a contract modification for continued risk-reduction activities was awarded in July 2016. Both risk-reduction activity efforts aid in further defining detailed requirements and design trade-offs required to support an informed decision that will lead to a lower-risk engineering and manufacturing development program. The Air Force obtained Milestone B approval in August 2016, which formally initiated the PAR program, authorized the purchase of two commercial aircraft, and approved the release of a Request for Proposal to cover efforts in the Engineering and Manufacturing Development phase that will result in the modification and testing of two Boeing commercial 747-8

aircraft. These aircraft are to be fielded in the 2024 timeframe to meet Presidential airlift requirements.

The Air Force inducted the second C-5C to undergo the Reliability Enhancement and Re-engining Program (RERP) modification; the C-5C aircraft are used to transport outsized NASA cargo. Upon completion of RERP, the Air Force plans to redesignate 49 C-5Bs, one C-5A, and two C-5Cs as C-5Ms, indicating increased range, payload, takeoff thrust, climb performance, and fuel efficiency, as well as an extended service life until at least 2040.

The Air Force Research Laboratory (AFRL) Adaptive Engine Technology Development (AETD) program successfully completed core detailed design reviews and numerous risk-reduction efforts. Key deliverables include an acquisition-quality engine preliminary design and critical risk-reduction testing of adaptive fans and core components by 2017.

The Supersonic Turbine Engine for Long Range (STELR) program will complete its testing in FY 2017. This program is a research test bed for future high-speed technology with a goal of achieving Mach 3 or higher in an engine test. Various risk-reduction efforts were completed at AFRL in FY 2016, and the program is scheduled to end with engine tests in FY 2017.

A successful and low-cost demonstration of engine technologies has been performed in the Small-Component and Engine Structural Assessment Research (S-CAESAR) program using recycled small engines. The program tested advanced instrumentation, damping coatings, and seeded faults, successfully increasing technology maturation levels in an affordable test bed.

The U.S. Marine Corps (USMC) transitioned a third squadron to F-35Bs on June 30, 2016. The USMC also completed the first overseas deployment of the F-35B, marking the first trans-pacific F-35 crossing and permanent deployment of USMC F-35Bs in Japan. USMC AV-8B Harriers and F/A-18 Hornets conducted forward-deployed combat sorties for named operations from both fixed-based airfields and sea-based platforms. Harriers employed the Advanced Precision Kill Weapon System (APKWS) in combat operations for the first time. AV-8Bs have started the Link-16 modification to be completed over the next two years. EA-6B Prowlers continue to support joint combat missions in support of combat operations while forward-deployed.

Marine KC-130s deployed to support operations in both United States Africa Command (AFRICOM) and United States Central Command (CENTCOM) Areas of Operation. The KC-130J models are continuing Harvest Hawk upgrades to increase fuel and cargo capacity while supporting sensor, weapon, and digital interoperability on the battlefield. The Marine Corps has accepted 62 percent of the KC-130Js ordered (49 of 79 aircraft). The KC-130J is a workhorse aircraft that has been continuously deployed since 2005.

The transition from legacy P-3s to the highly capable P-8A is now approximately 50 percent complete. Over 40 aircraft have been delivered.

The Department of Defense (DOD) continued progress toward the completion of the System Development and Demonstration (SDD) phase of the F-35 Joint Strike Fighter (JSF). Flight testing for mission systems, flight science, and weapons integration continued for all three variants: the F-35A Conventional Take-Off and Landing (CTOL), the F-35B Short Take-Off and Vertical Landing (STOVL), and the F-35C aircraft Carrier Variant (CV). The U.S. Navy hosted its first live-fire demonstration to successfully test the integration of the F-35 with existing Naval Integrated Fire Control–Counter Air (NIFC-CA) architecture. Air Force F-35A and Marine Corps and United Kingdom F-35B aircraft completed transatlantic flights to participate in air shows in England. F-35C aircraft completed Developmental Test 2 (DT-2) aboard the USS Dwight D. Eisenhower in October 2015, completing 66 catapults and arrestments. The F-35C also completed sea trials aboard the USS George Washington, which included the first operational fleet pilots completing carrier qualifications. The Air Force declared Initial Operational Capability (IOC) for the F-35A on August 2, 2016. A rollout ceremony for the first Israeli F-35 aircraft was held in September 2016. Naval pilots tested the Maritime Augmented Guidance with Integrated Controls for Carrier Approach and Recovery Precision Enabling Technologies (MAGIC CARPET) new precision aircraft-recovery system by safely landing on board the USS George W. Bush at sea. This system will reduce pilot workload, reduce landing variability, and improve carrier touchdown performance and safety even in adverse conditions.

Rotorcraft

The Marine Corps conducted its first flight of the CH-53K (Heavy Lift) King Stallion in FY 2016. The CH-53K entered its flight test phase after successfully completing hover tests at the Sikorsky Flight Center, setting the stage for expanding the fleet's ability to move Marines and materiel rapidly throughout an expanded mission area by 2019. The CH-53K successfully completed an external lift of a 27,000-pound payload at Sikorsky's Development Flight Test Center in West Palm Beach, Florida, on June 16, 2016. The aircraft executed an "out-of-ground effect" (OGE) external load test at 100 feet above the ground while performing hover maneuvers to demonstrate its excellent control-authority in this flight regime.

After conducting the Super Stallion Independent Readiness Review, the CH-53E community launched its readiness recovery effort, of which the main deliverable is the reset of all 146 of its aircraft. The CH-53E community has supported multiple Marine Expeditionary Units (MEU), the Special Purpose Marine Air Ground Task Force–Southern Command (SPMAGTF-SC), and the Unit Deployment Program (UDP) in Japan.

The VH-92 Presidential Helicopter Program completed its System-Level Critical Design Review in July 2016. Work continues on the two Engineering Development Models and the Mission Communications System.

The Marine Corps continues to transition its Medium Lift platform to the MV-22B. The transition is 75 percent complete, with all previous CH-46E squadrons in some form of transition. MV-22Bs are still being delivered from the factory, with 284 delivered out of a Program of Record of 360. The community conducted its Independent Readiness Review in order to better the institutional readiness of the fleet. The MV-22B is the Marine Corps's highest-in-demand platform and is supporting three MEUs and two SPMAGTFs; furthermore, it is preparing to support the Marine Rotational Force–Darwin this spring with the VMM-268, which moved to Hawaii in 2016.

The Army made significant improvements in joint interoperability and lethality capabilities for its AH-64E v4 attack reconnaissance aircraft. Fielding Link-16 and Air-to-Air-to-Ground (AAG) video relay allows the AH-64E to interoperate in joint environments with enhanced situational awareness. Further advancements

in precision weapons increased lethality with small guided munitions (SGMs) and Longbow L7A radar missiles. SGMs increased the stored number of precision hits by over 400 percent while abating collateral damage. L7A missiles incorporate new software and hardware to better acquire littoral and unmanned aircraft system (UAS) targets and defeat them with proximity fuse and fragmentation capability.

The Army began the process of developing and acquiring an updated version of the CH-47 that will improve the ground commander's ability to move soldiers and equipment across the battlefield. The CH-47 Block II will restore payload capability previously lost to additional armor and critical systems while also providing a feasible and affordable path for future upgrades. Finally, the convergence of Special Operations Command (SOCOM) and conventional H-47 designs will provide the Army with a helicopter capable of meeting the cargo lift needs of the warfighter well into the future.

The Army continues to complete fielding of the UH-60M to the Active Duty force and to selected Army National Guard and Army Reserve units. The UH-60M aircraft provides increased lift, digital avionics, and flight control coupling, reducing workload for the aviators while also providing more lift for the supported unit. The Army is considering upgrading remaining legacy Blackhawks (UH-60A/Ls) with the UH-60V, providing our aviators with a digital cockpit similar to the UH-60M's and therefore divesting all remaining analog cockpits from the Army Aviation inventory.

The Army continues to work with the Marine Corps and Special Operations furthering the development of the Joint Multi-Role Technology Demonstrator (JMR TD). JMR TD allows industry to demonstrate emerging technologies, reduce risk, and ultimately inform acquisition decisions regarding the future of vertical lift. The JMR TD is composed of two parts: Air Vehicle Demonstrator (AVD) and Mission Systems Architecture Demonstrator (MSAD).

The JMR AVD is developing two different aircraft, a tiltrotor and a lift-offset compound helicopter. In 2016, the Army's industry partners started the fabrication of components and assembly of major subsystems. Other rotary wing technologies include a compound rotorcraft concept with twin-ducted fans and an optimal-speed tiltrotor design. Flight demonstrations are scheduled to begin in 2017. The JMR AVD aircraft are designed to carry 12 troops, hover OGE at an ambient

condition of 6,000 feet and 95 degrees Fahrenheit, self-deploy to a range of 2,100 nautical miles, and fly at speeds of up to 230 knots. The joint service and DOD JMR MSAD are developing DOD standards, processes, and tools necessary to design and implement a mission systems open architecture to enable future modernization from competing industrial partners.

The Army's Advanced Affordable Turbine Engine (AATE) Science and Technology program transitioned to the Improved Turbine Engine Program (ITEP) in 2016. Results from the AATE program included demonstrated improved engine critical component technologies, advanced internal aerodynamics, hybrid ceramic bearings, and improved inlet particle separation. ITEP will develop a 3,000-shaft-horsepower-class engine that will fit within the current Black Hawk UH-60 and Apache AH-64 helicopter engine bay at similar weight. ITEP enables improved performance capability at 6,000 feet and 95 degrees Fahrenheit, more engine power with greater fuel efficiency, and equal or better engine sustainability and reliability. The Army is developing two preliminary engine designs to be completed in 2018.

Other Army Aviation Activities

In FY 2016, the Army Science and Technology community continued to work with the Air Force and industry partners to advance the development of flight controls, sensors, and cueing required to allow vertical-lift systems to operate safely and effectively in degraded visual environments (DVE). The Army completed ground-based testing of eight industry-provided systems at Yuma Proving Ground in Arizona. The tests assessed imaging systems' ability to collect, fuse, and present a discernable image of a populated obstacle field, obscured by blowing dust. The Army plans to further refine and integrate the systems for flight testing in 2016. The Army also demonstrated a new version of Modernized Control Laws for the Black Hawk that further improves flight performance and reduces pilot workload in DVE as part of testing at Moffett Field, California. Finally, the Army completed the first of a series of cueing experiments to investigate the contributions of visual, aural, and haptic cueing elements to optimize human performance in DVE.

In FY 2016, the Army continued executing the Aviation Restructure Initiative (ARI). The ARI is the Secretary of Defense–approved plan to provide a modernized

and ready aviation force while also reducing force structure in response to the Budget Control Act of 2011. It began in 2013 and is scheduled for completion in 2019. The restructured aviation force is smaller; however, it remains modernized, ready, and tailored to meet mission demands across the Active, Reserve, and National Guard components. The most significant changes included the divestiture of all Bell OH-58 variant aircraft from the Army, the transfer of select AH-64 aircraft from the Army National Guard to the Active Duty, and adoption of the Light Utility Helicopter (LUH-72) Lakota aircraft at the United States Army's Flight School. With the divestiture of legacy aircraft and reduction in force structure, the Army was able to modernize their remaining fleet with the improved UH-60M, the CH-47F Block II, the AH-64E, and the integration of the MQ-1C Gray Eagle and RQ-7 Shadow UAS.

The Army leads the DOD Policy Board on Federal Aviation's UAS Subgroup and continues to advance technological and policy solutions that further DOD unpiloted aircraft integration into the National Airspace (NAS). These solutions ultimately increase airspace access to DOD uncrewed aircraft for operational and training purposes. Recent accomplishments include collaborating with the Federal Aviation Administration (FAA) to codify a Memorandum of Agreement that expands DOD UAS airspace access and establishes interagency coordination procedures. Additionally, this working body oversaw the testing and operational integration of a Ground Based Sense and Avoid (GBSAA) capability that serves as an alternative compliance method to meeting the FAA's see-and-avoid regulatory requirement. The Army's first GBSAA system was certified for operational use at Fort Hood, Texas, on September 26, 2016. The Army plans to install four more GBSAA systems to support Gray Eagle operations by the end of FY 2017.

The Army's Aerial Intelligence Surveillance and Reconnaissance (A-ISR) strategy provides a roadmap for modernizing its platforms while incorporating the most valued quick-reaction-capability platforms utilized from years of conflict. In 2016, the Army began fielding and deploying the Enhanced Medium Altitude Reconnaissance Surveillance System (EMARSS) as well as its first Intelligence and Security Command (INSCOM) Intelligence Surveillance and Reconnaissance (ISR)–configured MQ-1C Gray Eagle UAS. The Army also began modernizing the Airborne Reconnaissance Low (ARL) fleet with the more sustainable DHC-8

aircraft. The Army will continue to modernize the A-ISR fleet in the coming years to provide increased capabilities while reducing the overall number of ISR aircraft in the inventory.

Modeling and Simulation

In FY 2016, the Army released its Helios v6 modeling and simulation software for rotorcraft aeromechanics. In addition to its existing capabilities for high-fidelity simulations of full-vehicle rotor and fuselage combinations, Helios v6 added a new option to include NASA's Fully Unstructured Navier-Stokes 3-Dimensional (FUN3D) code (a suite of computational fluid dynamics simulation and design tools) as a Helios near-body unstructured-grid flow solver. This FUN3D flow-solver option in Helios v6 builds on the earlier coupling of NASA's OVERset grid FLOW solver (OVERFLOW) structured-grid code as a near-body flow-solver option in Helios v5. The inclusion of NASA's OVERFLOW and FUN3D in Helios allows for faster, more accurate, and more robust simulations of the aerodynamics of rotors, fuselages, and rotor wake systems.

The Army has developed and validated a novel simulation architecture, which allows piloted (or autonomous), real-time, full flight-envelope simulation of aircraft and rotorcraft based on a collection of individual point models and trim data. The data needed to configure this model can be readily extracted from flight test results or high-fidelity non-real-time models. This novel simulation concept, referred to as a "model stitching simulation architecture," is applicable to virtually any aircraft configuration and has recently been applied to simulate the dynamics of a business jet and a utility helicopter. While the stitched model is developed for a nominal configuration, extrapolation methods within the simulation architecture permit accurate simulation without additional test data of off-nominal loading configurations, including variations in weight and center of gravity, as well as variations in altitude. This capability greatly minimizes the required number of flight test point models for full-envelope simulation.

Strike Weapons

In June 2016, the Joint Standoff Weapon C-1 (JSOW C-1) achieved Initial Operational Capability. The C1 variant adds network enabled weapon capabilities;

a two-way data link allows a controlling platform to update targeting information, among other new features. These features, along with the infrared (IR) seeker, give this variant enhanced maritime target capabilities. The initial hosting platform is the F/A-18E/F (Super Hornets); the weapon is currently being qualified on the F-35A/C to become operational in a future software block.

Collaborative Operations in Denied Environment

The Collaborative Operations in Denied Environment (CODE) program focuses on developing an uncrewed air system modular software architecture that will enable collaborative autonomous behaviors in multiple existing and legacy platforms that, by design, do not have collaborative autonomous capabilities. In November 2015, CODE successfully demonstrated formation flight behaviors with four small UAVs. Leveraging CODE, unpiloted vehicles are able to continuously evaluate their own states and gauge environmental changes. CODE-equipped uncrewed systems operate with minimal supervision and adapt to dynamic situations such as attrition of friendly forces or the emergence of unanticipated threats. The software for CODE is being developed in an open architecture adhering to emerging DOD standards and is designed to be platform-agnostic. Other key design features are resilience to bandwidth limitations and communications disruptions while being compatible with existing standards.

Aircrew Labor In-Cockpit Automation System

The Aircrew Labor In-Cockpit Automation System (ALIAS) program is developing a tailorable, drop-in kit that would add high levels of automation into existing aircraft, enabling operations with reduced on-board crew. The program seeks to reduce operator workload, reduce the training burden, augment mission performance, and improve aircraft safety. In December 2015, the ALIAS program successfully executed a fully integrated demonstration highlighting the ability to rapidly codify flight procedures; leverage perception systems to build a complete model of both cockpit and aircraft state; and use of add-on, in-cockpit actuation to drive both primary and secondary flight controls. The successful testing also validated the in-flight user interface. As an automation system, ALIAS supports the execution of the entire flight mission from takeoff to landing, even in the face

of contingency events such as aircraft system failures. ALIAS attributes, such as persistent-state monitoring and rapid recall of flight procedures, further enhance flight safety. Further testing in February 2016 showed the ability to operate an aircraft from takeoff to landing with all control being passed through a simple in-cockpit tablet interface.

Vertical Take-Off and Landing Technology Demonstrator

The Vertical Take-Off and Landing (VTOL) technology demonstrator program will develop technologies to enable revolutionary improvements in (heavier-than-air) VTOL air vehicle capabilities through the development of subsystems, aircraft configurations, and design integration. The program's target goal is to build and flight test an unpiloted aircraft weighing approximately 12,000 pounds, capable of sustained speeds in excess of 300 knots while enhancing hover and cruise efficiencies. In March and June 2016, the program successfully completed subscale first flight and subscale demonstrator development activities. This was a critical milestone in validating the flight control systems in flight. Other key highlights include a first-ever all-electric tilt-wing distributed ducted-fan propulsion system with the incorporation of flight-worthy 3D printed parts.

Automatic Collision Avoidance Technologies

The Automatic Integrated Collision Avoidance System (Auto ICAS) algorithms were tested by the AFTC at Edwards Air Force Base from May through September 2016, during which 11 single-ship and 16 two-ship flights were flown. Auto ICAS incorporates the legacy Automatic Ground Collision Avoidance System (Auto GCAS), which has been fielded on the Block 40/50 USAF F-16s and the recently developed Automatic Air Collision Avoidance System (Auto ACAS). The team is currently analyzing the data from the first phase of testing and plans to update the algorithms based on any issues found.

Hybrid Technology Program

Pre-Block 40 versions of the F-16s have analog flight control systems that are unable to host the Auto GCAS/Auto ACAS software. An AFRL, Lockheed Martin, and BAE Systems team has developed a hybrid technology that inserts digital processor modules into the analog flight control computer and makes the upgrade feasible and affordable. The Auto GCAS capabilities of the hybrid system have been tested on Norway's pre-Block 40 F-16 at Edwards AFB by the AFTC. Two phases of flight testing were completed between April 2015 and March 2016. There were 29 total flights of the system that proved that the updated Hybrid Flight Control System did not change the flying qualities of the aircraft, and it was determined that Auto GCAS on the Hybrid Flight Control System performed very similarly to Auto GCAS on the Digital Flight Control System. Based on the results of this effort and support from Air Force leadership, a Hybrid Technology Follow-on Effort has been started to 1) modify the Handling Qualities Simulation to F-16 Block 30 avionics configuration; 2) build, test, and qualify Hybrid Flight Control Systems that are specific to Air National Guard/Air Force Reserve Command aircraft; and 3) flight test the USAF F-16 Block 30 configuration in order to mature the technology to TRL 7 for transition to the F-16 program office. This Hybrid Technology Follow-on Effort started in August 2016 and is scheduled to run through June 2018. Once this effort is complete, the F-16 program office will integrate this technology on more than 300 USAF pre-Block 40 F-16s at the end of 2020. In addition to facilitating the fielding of Auto GCAS in these older USAF F-16s, the hybrid flight control computer enables the installation of other advanced functions as well as the fielding of Auto GCAS on F-16s flown by foreign partners.

Aerospace Vehicles

Sensitivity Analysis for Multidisciplinary Systems (SAMS) is a three-year joint Air Force-NASA project initiated in November 2015 to develop a high-fidelity capability to compute aeroelastic sensitivities for aerospace vehicle design. Computation of sensitivity analysis is critical to accounting for realistic physical constraints earlier in the design process. This way, problematic aircraft

configurations can be weeded out early in system development, before large investments are made, and new technologies can be assessed in terms of their system-level impact. SAMS has broad applicability, including to aero-structural efficiency concepts, controllability assessments for tailless supersonic configurations, and condition-based maintenance scheduling based on usage variations.

The product of the collaborative effort is to modularize and add analytical capability to the existing NASA LaRC Computational Fluid Dynamics (CFD) production code FUN3D. The FUN3D code is a national analysis standard developed over 25 years that possesses unique capabilities and has a very broad user base.

The objective of the Higher Bypass Ratio Inlet Development (HIBRID) Inlet Integration Demonstration (HIID) advanced inlet/commercial fan low-speed test at NASA Glenn Research Center's 9- by 15-foot wind tunnel was to determine the capabilities of an advanced commercial fan to handle spatially complex distortion patterns with combinations of distortion (swirl, steady state, and dynamic total pressure). The HIID test completed eight test phases in November 2015. The phases included fundamental distortion screens, fundamental bulk swirl vanes, paired swirl vanes, advanced inlet, advanced inlet with alternate geometry, severe fundamental and combined distortion screens, fundamental distortion screens combined with fundamental swirl patterns, and severe fundamental bulk swirl. The test program achieved 14 instances of fan-rotating stall with the other speedlines ending in stress limits or upon reaching the previously determined stability limit line. Thirty-one physical configurations were tested, including 13 advanced inlet configurations. This test program was a first-ever in terms of the thoroughness of the investigation of inlet distortion and the impact on a commercial fan. The levels of fundamental total pressure distortion and fundamental swirl distortion, along with the fundamental and complex combinations of these distortions, are not known to have previously occurred.

A small scale Hybrid Wing Body (HWB) model was tested in January 2016 in the Lockheed Martin Low Speed Wind Tunnel in Marietta, Georgia. The four percent–scale future strategic transport model had a 9-foot, 4-inch span. The objective was to develop the low-speed stability and control performance databases for a potential larger-scale HWB flight demonstrator. This testing complemented the 2015 subsonic-speed wind tunnel test at the NASA National Transonic Facility

(NTF), which used the same four percent–size model. The test was an evolution of the HWB transport design developed under Air Force and NASA aircraft efficiency design programs.

Hypersonics

The Office of the Secretary of Defense (OSD) Conventional Prompt Strike (CPS) effort executed technology development during FY 2016 for risk reduction in several key areas, including hypersonic aerodynamics, thermo-structural physics, and test and evaluation. Risk-reduction and technology-maturation efforts continued through ground tests to improve state-of-the-art modeling and simulation capabilities and technology readiness. Trade studies were conducted to evaluate system alternatives, affordability, and end-to-end system concepts. A CDR was completed for a future hypersonic flight experiment that will serve as a demonstration and evaluation of the latest technologies. These activities and data will be used to inform a potential acquisition program.

The AFRL partnered with NASA Langley Research Center and NASA Glenn Research Center on hypersonic research in 2016. AFRL in-house resources, combined with funding provided to NASA, enabled near-term expendable weapons and far-term reusable vehicles for atmospheric flight and access to space. Accomplishments from this arrangement include CFD analysis of the X-51A internal and external flow fields, hardware development for the Medium Scale Critical Components program, and testing and analysis to characterize the mode transition from turbine to ramjet operation.

Unmanned Aircraft Systems

The United States Air Force is executing the RQ-4 Global Hawk Program to provide continuous, high-altitude, long-endurance, all-weather, day/night wide-area surveillance and reconnaissance capability. The Global Hawk core program is in the final portion of the aircraft production and deployment phase, with an expected completion in FY 2018. In 2016, the program exceeded 200,000 flight hours and shifted focus to planning and executing a series of modernization efforts,

including new sensor integration, ground segment modification, operational flight program updates, and ice protection.

The United States Navy continued development of the MQ-4C Triton Unmanned Aircraft System (UAS) in FY 2016. In September 2016, the program received approval from the Under Secretary of Defense for Acquisition, Technology, and Logistics to initiate Low Rate Initial Production of MQ-4C aircraft and development of aircraft and ground segment modifications to add more sensor capabilities.

The U.S. Marine Corps began fielding the RQ-21 Blackjack to the first operational squadron in FY 2015. In addition to the Marine Corps's currently fielded RQ-7Bs, the Marine Corps began fielding the RQ-21 Blackjack to squadrons to support MEUs afloat, Marine Special Operations Command (MARSOC) units, and other Marine Corps regimental-sized units. The RQ-21 Blackjack supported its first MEU deployment in 2016.

The Army continues to modernize the MQ-1C Gray Eagle and RQ-7B Shadow UASes in stride with combat operations. The Army fielded its 11th Gray Eagle Company in August and enhanced the system with the introduction of a server-based Universal Ground Control Station (UGCS). In addition, production of the new Improved Gray Eagle began, which will extend the endurance of the aircraft by more than 50 percent. The RQ-7 Shadow is undergoing modernization with the fielding of the UGCS and the upgrading of existing data links to modern Ku-band Type 1 National Security Agency (NSA) encryption. The Shadow, which is primarily assigned to the Brigade Combat Teams and Special Forces Groups, is being integrated into the Combat Aviation Brigades as part of the Apache Helicopter Heavy Attack Reconnaissance Squadrons and the Army Aviation Restructure Initiative (ARI).

The MQ-8C Fire Scout UAV completed a three-week operational assessment (OA) at Naval Base Ventura County in Point Mugu, California. The OA included 11 flights totaling 83.4 flight hours, during which where Fire Scout was tested against maritime and surveyed land targets to assess the system performance, endurance, and reliability of the unmanned helicopter. The MQ-8C is intended to provide up to twice the endurance and three times the payload of the MQ-8B.

AFRL has continued the development and flight demonstration of a Sense and Avoid (SAA) airborne system for the safe integration of piloted and uncrewed air systems. The capability includes automatic detection and avoidance of air traffic with the ability to comply with emerging MOPS for the National Airspace System (NAS). Furthermore, AFRL is supporting NASA and the FAA in the development of MOPS for Remotely Piloted Aircraft (RPA) integration into the NAS for groups 4 and 5. AFRL continues the development of a comprehensive SAA capability for automated surface, terminal area, and "up and away" flight. Additional research is focused on SAA for future operations in military airspace.

AFRL Power and Thermal Management

An AFRL/Aerospace Systems Directorate (AFRL/RQ) in-house team completed dynamic thermal models to provide end-to-end assessment of the F-22 life-support and thermal management system (TMS) that provides the capability to assess the performance of the F-22 Environmental Control System (ECS) and On-Board Oxygen Generation System (OBOGS) during flight. This was funded by the F-22 System Program Office (SPO) in response to an AF Scientific Advisory Board (SAB) recommendation. AFRL/RQ led this model development effort as part of the F22 Life Support System Task Force chartered to identify root causes for physiological unknowns and implement corrective actions. The model includes the OBOGS and the ECS and provides the capability to predict their performance during varying flight conditions. Ultimately, the model predicts the quantity and quality of breathing gas available to the pilot during mission maneuvers.

AFRL/RQ has developed a Vehicle Systems Model Integration (VSMI) architecture for the F-35, which has been established at AFRL/RQ, the Lockheed Martin Aeronautics Company, and Naval Air Systems Command (NAVAIR) Patuxent River. VSMI extends the dynamic analysis capabilities of the F-35 program to address adaptive, on-demand systems and evaluate technology insertion options. Specifically, the VSMI architecture for the TMS enables the direct integration of the engine, engine fuel TMS (EFTMS), airframe TMS (AFTMS), and power and TMS (PTMS) models simultaneously with dynamic boundary interactions, allowing for a quick turnaround for architecture trade studies.

AFRL/RQ has successfully developed both a hardware laboratory capability and software models for an integrated power and thermal management system with an emulated directed energy (DE) load. The demonstration investigates blending power from a generator coupled to an emulated turbine engine and a battery system through a 270-volt direct current (DC) power bus into a 430-kilowatt dynamic load emulator that represents the DE load. Integrated modeling of the system was utilized to predict transient performance, to investigate and correct stability problems, and to develop a power-sharing control scheme to enable power blending between an emulated turbine engine and a battery system.

The AFRL INtegrated Vehicle Energy Technology (INVENT) Program has completed all unit testing and three out of five planned subsystem tests in preparation for two integrated ground demonstrations (IGDs). The testing evaluates the power and thermal architecture concepts, unit technologies, and modeling and simulation development to ultimately enable high-power mission systems on next-generation tactical aircraft through AFRL/RQ's Megawatt Tactical Aircraft (MWTA) Program. Results thus far indicate that the core architectures are sound, applicable unit hardware components can be made available for the integrated designs, and the modeling and simulation tools are suitable for further development required under the MWTA Program.

AFRL Space Vehicles Directorate

AFRL used NASA Van Allen Probes space science mission data to improve the standard radiation belt specification used to design commercial, Government, and DOD spacecraft. The specification is used to establish system survivability in the natural space radiation environment, and the improvements allow for more precise shielding and better risk assessment.

AFRL completed a prototype sensor to enable future satellites to include energetic particle sensing. The small, affordable sensor will allow rapid and accurate attribution of environmental impacts to DOD spacecraft to support the Space Mission Force in countering threats to U.S. space assets.

Airborne Weapons Systems and Missiles

The Air Force Ground Based Strategic Deterrent (GBSD) team's accomplishments included working with the Navy to understand the level of common work between Intercontinental Ballistic Missiles (ICBMs) and submarine-launched ballistic missiles; recently, the team received the Air Force Requirements Oversight Committee's approval of the GBSD program's draft Capabilities Development Document (CDD). All these activities supported a decision to enter the Technology Maturation and Risk Reduction (TMRR) phase of the project in FY 2016. The CDD provides a requirement threshold and objective values to take forward into the post-Milestone-A TMRR acquisition phase as the program evaluates and matures technologies that will be utilized in this future ICBM system that will replace Minuteman-III in the late 2020s.

In 2016, an array of improved weapon systems and munitions were considered within Army Aviation. Technologies include smaller, lighter, and more lethal munitions with improved accuracy, allowing aviation platforms to carry more kills per platform Two particular munitions the Army is employing and/or furthering technology for include 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 (PP) and Fire and Forget (F&F) targeting. The combination of Fire and Forget and Precision Point targeting capabilities enables improvements in the use of single-mode laser or radar air-to-ground missiles in adverse weather and against countermeasures while also affording simultaneous engagements on both moving and stationary targets with increased lethality.

APKWS II is a Semi-Active Laser (SAL) precision point guidance system that provides precision engagements affording low collateral damage against lightly armored and soft-point targets. The APKWS II guidance system is mated to the legacy unguided aerial rocket to provide air-to-ground suppression, smoke screening, illumination, and direct and indirect fires to defeat area materiel and personnel targets at close and extended ranges.

Space Activities

Launch and Range Operations and Spacelift Developments

The Evolved Expendable Launch Vehicle (EELV) program continued to successfully place satellites into orbit during FY 2016. United Launch Alliance (ULA) continued its record of success, with seven National Security Space (NSS) launches as of August 15, 2016. These launches included two Global Positioning System (GPS) IIF launches and the final Mobile User Objective System (MUOS) launch for the U.S. Navy.

Summary of Eight EELV NSS Launches During FY 2016

Date	Launch Vehicle Configuration	Payload
October 8, 2015	Atlas V (401)	National Reconnaissance Office Launch (NROL)-55
October 31, 2015	Atlas V (401)	GPSII-F 11
February 5, 2015	Atlas V (401)	GPS IIF-12
February 10, 2016	Delta IV (5,2)	NROL-45
June 11, 2016	Delta IV Heavy Lift Vehicle (HLV)	NROL-37
June 24, 2016	Atlas V (551)	MUOS-5
July 28, 2016	Atlas V (421)	NROL-61
August 19, 2016	Delta IV (4,2)	AFSPC-6 (Air Force Space Command Geosynchronous Space Situational Awareness Program [GSSAP] vehicles 3 and 4)

On October 9, 2015, the Air Force updated the Falcon 9 Launch System baseline configuration from the Falcon 9 v1.1 to the Falcon 9 Upgrade. The Space Exploration Technologies Corporation (SpaceX) Falcon 9 Launch System remains certified and eligible for award of NSS missions. On April 27, 2016, the Air Force awarded the first competitively sourced NSS launch services contract in more than a decade. SpaceX was awarded a contract for GPS III Launch Services.

In January and February 2016, as part of the development of a next-generation rocket propulsion system that will transition the Department of Defense away from the use of the Russian-supplied RD-180 engine to a domestic alternative for NSS launches, the Air Force entered into four other transaction authority (OTA) agreements with industry for the development of rocket propulsion system prototypes

for the EELV program. OTA agreements were used in lieu of standard procurement contracts in order to leverage ongoing investment by industry in rocket propulsion systems.

Range modernization efforts continued in FY 2016 with the following accomplishments:

(1) 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 IPv6.

(2) Construction began on a new Range Communication Facility (RCF) at the Eastern Range. The purpose of the new building is to relocate communications capabilities from the XY building to a new RCF, resolving building degradation, code noncompliance, and a high risk of flooding. The Air Force will either move existing equipment or procure new commercial equipment as necessary to meet system requirements and minimize impacts to scheduled launches.

(3) The Oak Mountain telemetry antennas at the Western Range completed acceptance testing on July 21, 2016, and were turned over to operations.

Position, Navigation, and Timing

The GPS program celebrated its 21st anniversary this year and continues to provide the gold standard of satellite-based, uninterrupted PNT data, free of charge, to users worldwide 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. Aboard Atlas V rockets, the Air Force orbited the final two IIF satellites in October 2015 and February 2016. All 12 IIF satellites are operating normally now, providing an increase in accuracy while having a longer design life than their predecessors. Besides the legacy signals, these Block IIF satellites will also provide the newest L2C and L5 civil signals. With eight launches over a 24-month period, this completed the most aggressive launch schedule since 1993. The arrival on

orbit of the IIF vehicles allowed the Air Force to remove from operations the final GPS IIA vehicle after 25 years of service to the world—well over three times the engineering design life. The IIF launches also helped us achieve 45 centimeters of user range error in April 2016, the best weekly performance of the navigation signal ever recorded.

The Air Force is currently completing development of the next generation of satellite vehicles (GPS III) and expects to have the first vehicle of that class available for launch in 2017. The first GPS III satellite completed final thermal vacuum testing in December 2015. Satellite vehicles 9 and 10 were placed on contract this year as technical equivalents of GPS III satellite vehicles 1 thru 8, ensuring continued and uninterrupted sustainment of the GPS constellation.

GPS satellite vehicle 23, launched in November 1990 and the oldest satellite in the GPS constellation, was finally retired in August 2016 after 25 years of on-orbit operations, more than tripling the design life of 7.5 years.

The existence of GPS and moving the GPS system to a dual military-civil system have created countless new industries for the United States and boosted its economy.

Satellite Communications

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. Production of AEHF satellite 4 is nearly complete, and launch is currently estimated to occur by November 2017.

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. The Command Post Terminal (CPT) variant was placed on contract for initial production runs in October 2015 and July

2016. The CPT will provide command and control of the AEHF constellation and provide command and control of nuclear forces to the President.

The second Enhanced Polar System (EPS) payload (on a hosted space vehicle) is being integrated onto its host spacecraft with an expected launch date in FY 2017. Operational testing is slated for FY 2018, 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 Wideband Global Satellite Communications (SATCOM) (WGS) satellite program consists of ten satellites with seven on orbit, WGS-8 planned for launch in December 2016, and WGS-9 and -10 in production. The first three satellites were part of the block 1 production; satellites 4 through 6 are part of block 2; and satellites 7 through 10 are termed block 2 follow-on. Each successive block provides greater capacity. WGS-7 launched on July 23, 2015, and became operational January 5, 2016. WGS is the DOD SATCOM constellation with the highest capacity and was declared 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 DOD X-band and Ka-band with flexible connectivity between bands and coverages to support and connect users operating worldwide.

The Mobile User Objective System provides narrowband communications using two separate payloads: a legacy Ultra-High Frequency (UHF) capability and the new Wideband Code Division Multiple Access (WCDMA) payload that provides greater than ten times the system capacity of the current UHF Follow-On constellation. MUOS is designed to improve ground communications for U.S. forces on the move, and it will provide voice, as well as new video, data, and chat capabilities. The U.S. Strategic Command (USSTRATCOM) activated the MUOS-3 legacy UHF payload for operations on April 5, 2016. DOD launched MUOS-5, the on- orbit spare, on June 24, 2016. MUOS-5 had an anomaly with its Liquid

Apogee Engine that would have precluded reaching geosynchronous orbit. A corrective action plan for MUOS-5 was implemented to move MUOS-5 to a usable orbital position at 105 degrees west. The AN/PRC-117G radio terminal completed initial MUOS WCDMA Waveform Military Standard (MIL-STD) 188-187 Do-No-Harm (DNH) testing on July 12, 2016. USSTRATCOM approved MUOS WCDMA operations for Early Combatant Command Use (ECU) on July 15, 2016. USSTRATCOM activated the MUOS-4 legacy UHF payload for operations on August 14, 2016.

Indications and Warning

The Space Based Infrared System (SBIRS) provides missile warning and supports missile defense, technical intelligence, and battlespace awareness mission areas. The nominal constellation consists of four Geosynchronous Earth Orbit (GEO) satellites, two hosted sensors in Highly Elliptical Orbit (HEO), and associated ground elements. Operational acceptance of the Block 10 ground system will consolidate legacy Defense Support Program (DSP), SBIRS HEO, and SBIRS GEO satellite ground systems from three locations into one primary location and a backup. The primary operations location is the Mission Control System–2 (MCS-2) at Buckley AFB, Colorado, and the secondary operations location is the Mission Control System Backup–2 (MCSB-2) at Schriever AFB, Colorado. The consolidation provides a significant reduction in manpower requirements and allows for improvements in mission-processing capabilities. Operational acceptance of the Block 10 ground system occurred in December 2016.

Satellite Control and Space Situational Awareness

In August 2016, the Joint Space Operations Center (JSpOC) Mission System (JMS) completed its fourth of four developmental tests for Service Pack–9 (SP-9). Upon completion of operational testing and capability acceptance review, SP-9 will be delivered as an update to the operational system on the JSpOC floor in the spring of 2017 and will transition the authoritative catalog of space objects from the legacy database to JMS. SP-9 also enables significant new capabilities, including

the following: catalog growth to 1 million objects with future scalability, "all vs. all" conjunction assessment, automated and continuously updated high-accuracy orbit determination, and maneuver detection. JMS is an agile information technology development program, delivering capabilities in a series of increments. Increment 1 went operational in 2012 and has supported multiple high-profile events since inception. Increment 2, SP-7, has been in operation since November 2014.

Site construction for Space Fence Increment 1 continued as planned during FY 2016 on Kwajalein Atoll, Republic of the Marshall Islands, with more construction needed to reach testing milestones in FY 2017 and IOC in FY 2019. The Space Fence radar system will improve Space Situational Awareness (SSA) capabilities by providing un-cued surveillance of small objects and satellites in low- and medium-Earth orbit to provide spaceflight safety, early detection and custody of threats, and awareness to satellite operators in the crewed spaceflight regime.

The United States and Australia continue to work together in the SSA mission area. The C-Band Radar that was relocated from Antigua Island to Australia completed operational testing in September 2016. After IOC declaration in FY 2017, the radar will become the only U.S. near-Earth dedicated SSA sensor in the Southern Hemisphere. C-band radar provides excellent satellite detection tracking and identification capability, along with extremely accurate space object positional data and the ability to increase maneuver detection and conjunction assessment capabilities. Efforts also continue to operationalize the Space Surveillance Telescope (SST) located at White Sands Missile Range, New Mexico, prior to its relocation to Harold E. Holt Naval Communication Station in Exmouth, Western Australia. SST technology enables faster discovery and tracking of previously unseen, hard-to-find small objects in geosynchronous orbits. SST is another step forward with Australia and is a cornerstone to fulfilling SSA requirements to find, fix, track, and characterize deep space small objects. Australia will operate both the C-Band Radar and SST systems in partnership with the United States.

Nanosats and SmallSats

The Army Space and Missile Defense Command (SMDC)/Army Forces Strategic Command (ARSTRAT) Technical Center developed and is testing two

technology-demonstration programs designed to provide imagery and over-the-horizon communications directly to military units on the ground.

The first program is the SMDC Nanosatellite Program (SNaP). It is being developed as a cost-effective, responsive capability that will mitigate the impact of the loss or disruption of national space-based capabilities. SNaP is designed to deliver a more resilient space capability and is part of an initiative to explore technologies deployed on nanosatellites in low-Earth orbit with the goal of ensuring warfighter freedom of maneuvering, communication, and immediate access to actionable situational awareness information. SNaP has a propulsion system for stationkeeping and can be used for voice communication, data transfer (including short message service texting), and data exfiltration from unattended ground sensors. It is compatible with PRC 117 and PRC 152 radios, along with certain partner nation radios with Type 1 encryption (e.g., Harris 5800M). In October 2015, three SNaP nanosatellites were launched from Vandenberg Air Force Base, California. After launch and release from the main rocket body, the three SNaP satellites were diagnosed for status and functionality and subsequently tracked by SMDC/ARSTRAT ground stations.

The second program SMDC/ARSTRAT is developing is the Kestrel Eye spacecraft. Kestrel Eye is an electro-optical microsatellite-class imagery satellite for tasking by the tactical ground component warfighter. It is capable of producing tactically useful imagery. Kestrel Eye's data can be downlinked directly to the same warfighter via a data relay network that is also accessible by other warfighters in the theater without any continental United States relay. The Kestrel Eye program will extend the Army's Unmanned Aerial System paradigm into space, proliferating numbers of satellites and enabling the system to be dedicated to and operated by warfighters. Kestrel Eye is scheduled to be launched to the International Space Station as a part of a cargo resupply mission in fiscal year 2017.

Rocket and Missiles Propulsion

The AFRL Rocket Lab at Edwards Air Force Base (AFB), California, performed load operations of AF-M315E for the NASA Green Propellant Infusion Mission (GPIM). AF-M315E was developed by the AFRL Rocket Lab to be less toxic than

traditional chemical fuels like hydrazine, thus requiring fewer handling restrictions and less special equipment. The reduction in handling restrictions and special equipment could shorten launch processing times, resulting in lowered costs. On track for a 2017 launch, GPIM will demonstrate the practical capabilities of AF-M315E. The new propellant is 45 percent denser than hydrazine, meaning more of it can be stored in containers of the same volume. Coupled with a greater specific impulse (Isp) than hydrazine, this means there is approximately a 50 percent increase in spacecraft maneuvering capability for a given volume. AF-M315E also has a lower freezing point than hydrazine, requiring less spacecraft power to maintain its temperature.

Ground testing of the Hydrocarbon Boost Demonstrator subscale pre-burner was completed. Results were utilized to complete the final design of the full-scale pre-burner, a major component of the advanced liquid-oxygen/liquid-kerosene rocket engine. The subscale ground testing also demonstrated, for the first time, the survivability of the Mondaloy 200 superalloy in a high-pressure oxygen environment. The Hydrocarbon Boost Demonstrator pre-burner is being utilized in a Space and Missile Systems Center (SMC) and NASA thrust chamber combustion stability demonstration project, supporting SMC risk-reduction efforts for a new engine to be used in a future launch vehicle. The Hydrocarbon Boost Demonstrator full-scale kick pump began ground performance testing and reached full power. This is the first full-scale Hydrocarbon Boost Demonstrator component test, which also validated the use of design tools developed under the Upper Stage Engine Technology effort, for the first time, in a liquid-kerosene environment. The resulting technologies will enable and support future domestic space launches.

Other Space Developments

The Counter Communications System (CCS) provides expeditionary, deployable, 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. Program procurement funding was increased in FY 2015 to allow purchase of five new CCS systems for the Air National Guard. The preplanned product

improvements, which transition the system to Increment 10.2, are on track and progressing well. The first two deliveries are scheduled for mid-FY 2017.

In 2016, the Operationally Responsive Space (ORS) Office continued to support the on-orbit operations of the ORS-1 satellite, launched in June 2011 from NASA's Wallops Flight Facility, Virginia. Although designed with a life of two years, ORS-1 continued to support U.S. Central Command throughout FY 2016. Additionally, ORS continued to directly support Joint Force Commander needs with the development of ORS-5 to satisfy a U.S. Strategic Command need. The ORS-5 satellite will demonstrate SSA (wide-area search capability) of the GEO belt with a small satellite in low-Earth orbit. The ORS-5 satellite, scheduled to launch in 2017, will provide risk reduction to the Space Based Space Surveillance Follow-On (SBSS FO) program and will develop and demonstrate ORS enablers and principles. In November 2015, ORS launched ORS-4, the small, responsive, low-cost Super-Strypi launch vehicle. While the launch failed to achieve orbit, it demonstrated several of its mission objectives, including installing a rail launcher and launch pad, using a rail for an orbital launch, and launching from a reduced infrastructure range with a minimal crew. To support the long-term plan for meeting Weather Satellite Follow-on (WSF) requirements, the Air Force is pursuing a multi-phase effort. One of the first phases is the ORS-6 mission, a flight technology demonstration with potential residual operational capability of the Compact Ocean Wind Vector Radiometer (COWVR) payload mounted on the ORS Modular Space Vehicle (MSV) bus, leveraging the Modular Open System Approach (MOSA) and the Rapid Response Space Works (RRSW). The ORS-6 mission will measure ocean surface vector winds and tropical cyclone intensity and launch in November 2017.

The DOD Space Test Program provides spaceflight opportunities for militarily relevant DOD space research and development payloads. The program delivers innovative space system solutions for Air Force and DOD customers to enable flexible, resilient, and affordable capabilities. The Space Test Program is preparing for five different launch missions in 2017. These include nine payloads to enhance space situational awareness in the GEO belt; Kestrel Eye II to evaluate a low-cost electro-optical microsatellite; STP-2 to launch multiple experiments on a Falcon 9 Heavy; and STPSat-5 to develop, build, and fly a small, inexpensive space

vehicle to support the maximum feasible number of Space Experiment Review Board Experiments.

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 the past year, SSDP executed four experiments supporting stand-up of the Joint Interagency Combined Space Operations Center (JICSpOC) at Schriever AFB and conducted analysis on Space Situational Awareness and operational-level command and control of space assets in support of DOD Space Strategic Portfolio Review and Air Force Space Command's Space Enterprise Vision. SSDP continued work with the Combatant Commands (CCMD) on both developing validated response options and integrating cyber defenses into their operations and plans to protect and defend our space assets. Finally, SSDP conducted a number of analytic efforts focused on identifying characteristics of a resilient architecture in a contested environment. As a result of SSDP efforts, JICSpOC baseline operational interfaces and processes were established, space command and control and SSA requirements were documented, CCMD plans were revised, and key system resiliency trades for next-generation satellite communication and missile warning constellations were defined.

Federal Aviation Administration

FAA

The Federal Aviation Administration (FAA) achieved landmark milestones in its ongoing Next Generation Air Transportation System (NextGen) effort that is transitioning the National Airspace System (NAS) from analog and ground-based systems to cutting-edge digital and satellite-enabled technologies. The NextGen transformation 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—based on knowing where an aircraft is—to a time-based management system that operates on shared knowledge of where an aircraft will be at any given point in time along its projected trajectory. Time-based management will significantly increase efficiency and flexibility in the NAS and help achieve the NextGen goals of reduced delays, enhanced safety, decreased fuel burn, and fewer aircraft exhaust emissions. To enable these changes, the existing infrastructure must be either replaced or modified, and interfaces must be designed and put in place between different systems to ensure that they seamlessly communicate with each other.

NextGen is critical to protecting aviation's contributions to U.S. economic strength. A vibrant aviation industry is vital to the Nation's fiscal health, as civil aviation contributes 10.6 million jobs and $1.6 trillion a year to the U.S. economy. To date, the NextGen capabilities already deployed have delivered $1.6 billion in benefits to airlines and the traveling public. The FAA expects NextGen to deliver $160.6 billion in shared benefits through 2030.

Automation

Some of the FAA's biggest modernization gains in 2016 were in automation—the computer systems that controllers use to manage our Nation's air traffic. These systems are platforms upon which NextGen programs and capabilities are built.

Under the Terminal Automation Modernization and Replacement (TAMR) program, the FAA is replacing the Automated Radar Terminal System (ARTS) in Terminal Radar Approach Control (TRACON) facilities with the state-of-the-art Standard Terminal Automation Replacement System (STARS). TRACONs guide aircraft transitioning to and from high-altitude airspace. Four ARTS model IEs and 55 ARTS model IIEs remain in the NAS, with the numbers continuing to decline.

STARS also is replacing the automation in the FAA's largest TRACONs and is now operational at the 11 of them that control 80 percent of all U.S. traffic. Nine of those TRACONs are among the ten busiest air traffic facilities in the world. The TAMR program expects to fully deploy STARS to all TRACONs by 2020, enabling many NextGen technologies in terminal airspace, including Automatic Dependent Surveillance–Broadcast (ADS-B), a satellite-enabled technology that will serve as the FAA's primary means of aircraft surveillance, and the advanced Terminal Sequencing and Spacing (TSAS) function for Time Based Flow Management (TBFM).

The TAMR program's success mirrors the FAA's achievement in deploying the En Route Automation Modernization (ERAM) system to all 20 air route traffic control centers in the contiguous United States—a process that was completed 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 is supplementing voice communications with digital text-based messages exchanged between controllers and pilots.

Data Comm

In 2016, the FAA completed the deployment of Data Comm departure clearance services to towers at 56 airports. As a priority area identified by the Radio

Technical Commission for Aeronautics (RTCA) NextGen Advisory Committee, a Federal advisory committee composed of executives from across the aviation community, this deployment was completed more than two years ahead of schedule.

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 dispatchers simultaneously receive the same information. Flight crews signal concurrence with the press of a button; instructions can then be automatically loaded into the aircraft's flight management system. This process can be repeated as often as necessary from the gate until the aircraft is ready for takeoff. By providing an air-to-ground data link, this transformational program is a critical component of the FAA's NextGen vision of time-based traffic management.

With tower service in place, the FAA is preparing for the next step of adding en route services. The agency made its final investment decision and reached its cost, schedule, and technical requirements milestone for this phase in August 2016.

In economic benefits, Data Comm is expected to save operators more than $10 billion over the 30-year life cycle of the program and the FAA about $1 billion in future operating costs.

ADS-B

Aircraft flying in most controlled airspace must be equipped to broadcast their position using ADS-B Out by January 1, 2020. ADS-B Out—a basic level of aircraft equipage—relies on aircraft avionics, a constellation of GPS satellites, and a network of ground stations across the country to transmit an aircraft's position, ground speed, and other data to air traffic controllers. The Equip 2020 Government-industry working group is working to eliminate equipage impediments for commercial and general aviation operators. As of the end of 2016, nearly 25,000 aircraft have been equipped with ADS-B avionics.

While equipping with ADS-B In is not mandatory, operators who chose to install the necessary transceiver and cockpit display will benefit from seeing the same traffic picture as controllers, which significantly increases situational awareness. General aviation operators who equip with ADS-B In have the added

benefit of graphical weather and flight information delivered to the cockpit at no further cost.

In September 2016, to make the equipage decision easier, the FAA initiated a $500 rebate program to help general aviation operators defray ADS-B equipment and installation costs. U.S.-registered fixed-wing, single-engine piston aircraft that are not equipped with Version 2 of ADS-B Out are eligible. The rebates are being issued on a first-come, first-served basis for about one year from the launch or until 20,000 have been claimed, whichever comes first.

Performance Based Navigation

Performance Based Navigation (PBN) uses GPS/GNSS satellites and onboard equipment for improved navigation that allows more precise and accurate flight than that limited to standard avionics and ground-based navigation aids. PBN's name reflects that the types of routes and procedures an aircraft can fly depend on equipment performance level and pilot training.

The FAA already has published more than 15,000 PBN arrival, departure, and approach procedures as well as high- and low-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 point-to-point over ground-based navigation aids. In 2016, the FAA published the PBN NAS Navigation Strategy 2016 (available at *http://www.faa.gov/nextgen/media/PBN_NAS_NAV.pdf*), which outlines the agency's plans for moving to a PBN-centric NAS.

PBN's benefits include the following:

- Increased safety through repeatable and predictable flight paths.
- 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 airspace and closely spaced parallel operations procedures.
- Increased efficiency through more direct routes, especially at lower flight altitudes.
- Curved approaches.

PBN's Area Navigation and Required Navigation Performance (RNP) provide environmental benefits through reduced emissions and fuel consumption. In Denver alone, RNP approaches save Southwest, United, and Frontier airlines more than 100 gallons of fuel per flight.

Enhanced Low Visibility Operations

NextGen funded Phase II of Enhanced Low Visibility Operations (ELVO), which is actively allowing increased access to airports for air carriers in low-visibility conditions, such as those induced by fog. By assessing and providing a greater and more appropriate level of credit to the advanced avionics, ELVO allows a greater number of airports throughout the United States to have equivalent Category II capability with no or little investment. This helps the air carriers recoup the return on investment for these advanced avionics. Lower-than-standard departures are also allowed, helping reduce flight delays by allowing aircraft to depart in conditions that earlier would have caused delays and ground stops. ELVO has increased the number of on-time arrivals and departures in the NAS.

System Wide Information Management

To function smoothly, the NAS relies on users sharing an increasing amount of air traffic management data. System Wide Information Management (SWIM), an advanced technology program, turns NAS data into useful information for aviation stakeholders. The digital data delivery platform provides the foundation for fully implementing many NextGen operational improvements.

Replacing multiple stand-alone computer interfaces that connect point-to-point, SWIM provides a modern, universally recognized data-exchange format interface through a single connection. The new format supports collaboration within the domestic and international aviation communities, and users gain unprecedented access to data products with improved bandwidth and security. SWIM also contributes to the FAA's goal of time-based traffic management.

SWIM operates through an enterprise service-oriented architecture (SOA) composed of producers, subscribers, and a registry. Producers—in this case, FAA NAS

programs—publish data exchanged through the NAS Enterprise Messaging System for registered subscribers. Subscribers can access more than 100 SWIM products, which are categorized as aeronautical, flight and traffic flow, or weather. The FAA and SWIM subscribers—inside and outside the FAA—interact through a registry, where subscribers can search specific criteria to find services.

SWIM Segment II—aimed at establishing an enterprise SOA—was completed in 2016, one year after the first segment to establish a common infrastructure and connection points at all 20 air route traffic control centers was completed to transform point-to-point interfaces. SWIM Segment II also connected NAS programs to provide large data sources for subscribers, such as the Traffic Flow Management System (TFMS) and Integrated Terminal Weather System (ITWS). TFMS is a suite of automation tools used to help balance NAS traffic demand and capacity, while ITWS improves integration of weather data into timely, accurate aviation weather information. Both help reduce delays and improve NAS capacity.

It also attracts more subscribers interested in accessing the data.

Decision Support Systems

Air traffic controllers and traffic managers use decision support systems to help solve traffic flow constraints and optimize traffic flow across the NAS. In 2016, Integrated Departure/Arrival Capability (IDAC), a component of TBFM, was deployed to many busy control towers. IDAC automates departure demand monitoring and departure slot identification. It coordinates the departure times between airports and provides situational awareness to controllers so they can select from available departure times and plan their operations to meet those times.

The FAA received NASA's latest tool to help make NextGen a reality on July 14, 2016. Terminal Sequencing and Spacing, another element of TBFM, is designed to aid TRACON controllers in determining the optimal aircraft speed and position to stay on a fuel-efficient descent provided by PBN procedures. The goal is to enable all descending aircraft to safely merge into a point where they can transition to an airport tower controller for their final approach.

Another system significantly progressing this year is Terminal Flight Data Manager (TFDM). The FAA is completing early implementation of portions of

TFDM before full initial operating capability, which is scheduled for 2020. Advanced Electronic Flight Strips (AEFS) hardware was installed in September at Charlotte Douglas International Airport, North Carolina, to support Airspace Technology Demonstration 2 (ATD-2), a NASA-led project to integrate arrival, departure, and surface activities. AEFS replaces manual tracking with an electronic flight data display, which allows controllers to stay engaged with traffic at all times.

In TFDM, AEFS and the ATD-2 prototype tools integrate with other new technologies, such as the IDAC, a function in TBFM to coordinate schedules between the ramp and tower, terminal, and center control facilities, giving air traffic managers the tools to make better decisions about how to reduce congestion and increase efficiency.

Interagency Collaboration and UAS

Just as NextGen is transforming the NAS, unmanned aircraft systems (UASes) are bringing unprecedented new opportunities for business and recreation. Enabled by new technology platforms, the number of UAS pilots in the NAS has grown dramatically. The challenge is to ensure that these new aircraft are integrated with piloted 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 in the NAS. The FAA implemented new rulemaking to permit small UAS-limited operations in U.S. airspace. Additionally, the FAA announced a streamlined and user-friendly Web-based aircraft registration process for owners of UAS that weigh between 0.55 and 55 pounds, including payloads such as cameras.

The introduction of UAS affects existing and future aviation requirements from aircraft certification to air traffic management. NASA and the FAA have 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 unmanned aircraft systems can be found at *http://www.faa.gov/uas/*.

Commercial Space Transportation

As the FAA achieved tremendous success in its NextGen effort, its Office of Commercial Space Transportation (AST) continued moving forward in promoting U.S. commercial space transportation.

In 2016, AST licensed 11 orbital commercial space launches: three United Launch Alliance (ULA) Atlas V launches from Cape Canaveral Air Force Station (CCAFS) in Florida and eight SpaceX Falcon 9 launches from CCAFS. Under an experimental permit, Blue Origin conducted four suborbital commercial space launches of the Blue Origin New Shepard system from the company's test site in western Texas.

One AST licensed orbital operation ended in failure. In September 2016, the SpaceX Falcon 9 rocket and its associated payload, the AMOS-6 commercial communications satellite, exploded on the launch pad during preparations for a static test fire of the vehicle. This incident did not result in any third-party property damage. Additionally, there were no fatalities or injuries.

In FY 2016, AST issued a new Reusable Launch Vehicle (RLV) mission operator license to Virgin Galactic for conducting WhiteKnightTwo/SpaceShipTwo missions from Mojave Air and Space Port, California. Furthermore, AST granted several modifications to existing launch licenses in FY 2016. AST modified Orbital's launch operator license to reflect its reconfigured Antares rocket, SpaceX's launch license to reflect a new Falcon 9 launch vehicle version and allow first-stage fly-back that included the first return-to-launch-site landing, and SpaceX's reentry license to reflect changes to the Dragon reentry vehicle and the reuse of previously flown components. AST granted launch site operator license renewals to the Oklahoma Space Industry Development Authority in Tulsa and to the Harris Corporation for launches at the California Spaceport at Vandenberg Air Force Base.

AST renewed an experimental permit for SpaceX for flights of its Dragonfly Reusable Launch Vehicle at the company's McGregor Test Site in Texas. AST also renewed Blue Origin's experimental permit authorizing it to continue tests of the New Shepard vehicle at the company's western Texas site. AST did not issue any new safety approvals during the fiscal year but did renew the safety approval for SpaceTEC Partners, Incorporated, for its Aerospace Core certification and

advanced concentration certifications in aerospace vehicle process, aerospace manufacturing, and aerospace composites, as well as the safety approval for the Zero Gravity Corporation for its ability to provide a flight environment capable of replicating various reduced gravity levels.

AST conducted inspections at various locations, including Vandenberg Air Force Base, California; Burns Flat, Oklahoma; CCAFS, Florida; Decatur, Alabama; Pacific Spaceport Complex, Kodiak, Alaska; New Mexico Spaceport Authority, Las Cruces, New Mexico; McGregor Test Site, Texas; Orbital-ATK facilities, Dulles, Virginia; SpaceX facilities, Hawthorne, California; Ellington Field, Houston, Texas; Midland, Texas; National Aerospace Training and Research (NASTAR) facilities, Southampton, Pennsylvania; Jacksonville, Florida; Virgin Galactic, Mojave, California; and MARS, Wallops Island, Virginia.

In FY 2016, AST issued three environment-related documents. In December 2015, AST issued a Finding of No Significant Impact (FONSI) to adopt the United States Air Force October 2014 "Environmental Assessment for the Space Exploration Technologies Vertical Landing of the Falcon Vehicle and Construction at Launch Complex 13" at CCAFS in Florida; in March 2016, AST issued a FONSI to adopt NASA's September 2015 "Final Supplemental Environmental Assessment for the Antares 200 Configuration Expendable Launch Vehicle" at Wallops Flight Facility in Virginia; and, in April 2016, AST issued an Environmental Assessment and FONSI/Record of Decision (FONSI/ROD) for the Kodiak Launch Complex Launch Pad 3 in Alaska.

Also in 2016, the FAA continued support of its Center of Excellence for Commercial Space Transportation (COE CST), which enables the FAA to work with universities and their industry partners to conduct research in environmental and aviation safety, as well as other activities, to ensure a safe and efficient air transportation system. The COE CST, working with nine member universities, provides grants with a one-to-one matching requirement (one non-Federal dollar for every Federal dollar granted) in four distinct research areas: space traffic management and operations; space transportation operations, technologies, and payloads; human spaceflight; and space transportation industry viability.

In 2016, AST conducted a payload review of the Moon Express MX-1E lunar lander capable of transferring from Earth orbit to the moon, making a soft landing

on the lunar surface, and performing post-landing relocations through propulsive "hops." In July, the FAA made a favorable payload determination for the Moon Express MX-1E spacecraft/lander. The FAA has determined that the launch of the payload does not jeopardize public health and safety, the safety of property, U.S. national security or foreign policy interests, or international obligations of the United States. This is the first-of-its-kind payload determination for a spacecraft meant to visit the lunar surface. This action was seen as a step toward supporting commercial activities beyond Earth orbit.

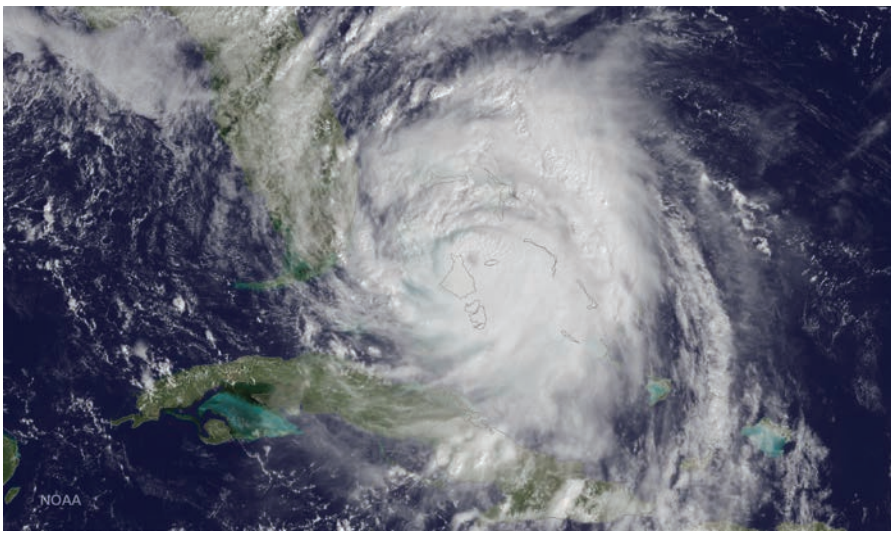
Additional information about the FAA Office of Commercial Space Transportation, regulations, reports, and other documents can be found online at *https://www.faa.gov/go/space*.

Department of Commerce

DOC

In January 2016, the National Oceanic and Atmospheric Administration (NOAA) released its Commercial Space Policy, which sets a broad framework for usage of commercial space-based approaches for the agency. The policy establishes critical components for engaging with the commercial sector, including designating the Office of Space Commerce as a single point of entry for commercial providers to streamline engagement; establishing an open and transparent marketplace; defining guiding principles, implementation considerations, and strategic planning for potential commercial data buys; and establishing demonstration projects to test and evaluate new potential data sources and provide an avenue to operational commercial data buys.

The Commercial Space Policy calls for NOAA to explore and pursue demonstration projects to validate the viability of adding commercial environmental data and products into NOAA's meteorological models. The Commercial Weather Data Pilot (CWDP) will serve as one such demonstration project, evaluating commercial data to demonstrate the quality of the data and their impact on weather forecast models, as well as informing NOAA's process for ingesting, evaluating, and utilizing commercial data in the future. During FY 2016, NOAA held an industry day, issued two public solicitations related to the CWDP, and awarded contracts to two U.S. companies for space-based commercial weather data. Under the contracts, the companies will provide GPS radio occultation data for the purpose of data demonstration. Radio occultation is a technique for performing key atmospheric measurements. The CWDP paves the way for future operational data buys in support of NOAA weather forecasting.



The Geostationary Operational Environmental Satellite (GOES) East satellite captured this image of Hurricane Matthew in the Bahamas on its way to the Florida coast at 1445 UTC on October 6, 2016.

In November 2015, Congress passed a law renaming the Department of Commerce's (DOC) Office of Space Commercialization as the Office of Space Commerce and updating the office's statutory responsibilities to include promoting U.S. geospatial technologies and providing support to the National Coordination Office (NCO) for Space-Based Positioning, Navigation, and Timing (PNT). At that point, DOC had already hosted the NCO for ten years, and it continued to do so in FY 2016. This included hosting the *http://www.gps.gov* Web site, a top result in Internet searches for "GPS." The NCO is the Secretariat of the National Executive Committee for Space-Based Positioning, Navigation, and Timing, the senior body that advises and coordinates Federal agencies on matters affecting GPS. DOC continued to serve as a member of that committee throughout FY 2016.

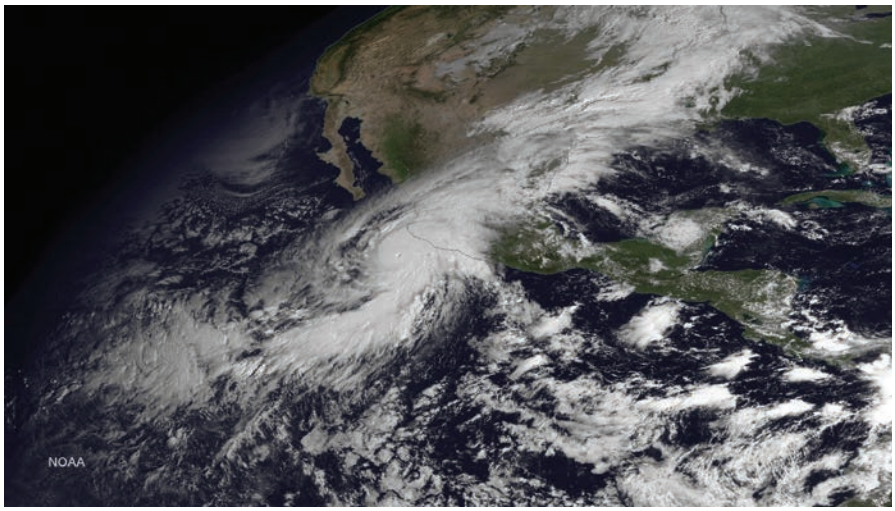
Also during FY 2016, DOC participated in various dialogues on satellite navigation and space cooperation with other nations and other entities, including Europe, China, and the International Committee on Global Navigation Satellite Systems. In March 2016, DOC cochaired a meeting of a U.S.-European working group on trade issues affecting GPS and Europe's Galileo satellite navigation system. DOC also supported a number of speaking engagements and other outreach activities to promote global understanding and use of the U.S. GPS.

National Oceanic and Atmospheric Administration

In FY 2016, the importance of NOAA's operational meteorological and environmental satellites remained as critical as ever as they monitored the severe drought and wildfires in the West, record heat in the Southwest, devastating flooding in Louisiana caused by over two feet of rain, and the planet's warmest year on record (2015, besting the previous record set in 2014). Twenty-four-hour global coverage from NOAA's satellites provides scientists, decision makers, and the public with a continuous stream of information used in preparation for events impacting our climate, weather, and oceans. NOAA 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.

NOAA's Geostationary Satellites

Geostationary Operational Environmental Satellite (GOES) satellites continuously monitor the Western Hemisphere by circling Earth in a geosynchronous orbit



The eye of Hurricane Patricia is visible on October 23, 2015, from GOES East. Patricia became the strongest hurricane on record in the eastern North Pacific and North Atlantic basins before making landfall on the coast of southwestern Mexico as a category 4 hurricane.

22,000 miles above the equator, meaning they remain over one position on the surface by orbiting at a speed matching that of Earth's rotation. GOES imagery and data help meteorologists with forecasting weather in the short term, tracking severe storms, and estimating precipitation for issuing winter storm warnings and spring snow-melt advisories. In FY 2016, GOES-15 flew at 135° west longitude and served as "GOES West," while GOES-13 flew at 75° west longitude and served as "GOES East." The newest generation of GOES launched in late 2016. Continuing 40 years of GOES coverage, the GOES-R satellite is more advanced than any other weather satellite of its kind and will provide more detailed and accurate data for forecasters.

NOAA's Polar-Orbiting Satellites

NOAA's primary polar-orbiting environmental satellites, Polar-orbiting Operational Environmental Satellites (POES) 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. POES 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 Suomi NPP satellite remained NOAA's primary operational polar-orbiting satellite. Suomi NPP is a joint NOAA-NASA mission and serves as a bridge between NOAA's current fleet of polar-orbiting satellites and the upcoming next-generation Joint Polar Satellite System (JPSS). JPSS-1 took a major step forward on its journey to launch as its fifth and final instrument, the Advanced Technology Microwave Sounder, was integrated with the satellite. The spacecraft entered the environmental testing phase, the next step toward launch. NOAA-19, NOAA's previous primary operational polar-orbiting satellite, also remains a critical part of NOAA's polar constellation and provides valuable contributions to National Weather Service forecasts.

April 15, 2016, marked the ten-year anniversary of the launch of the Constellation Observing System for Meteorology, Ionosphere, and Climate

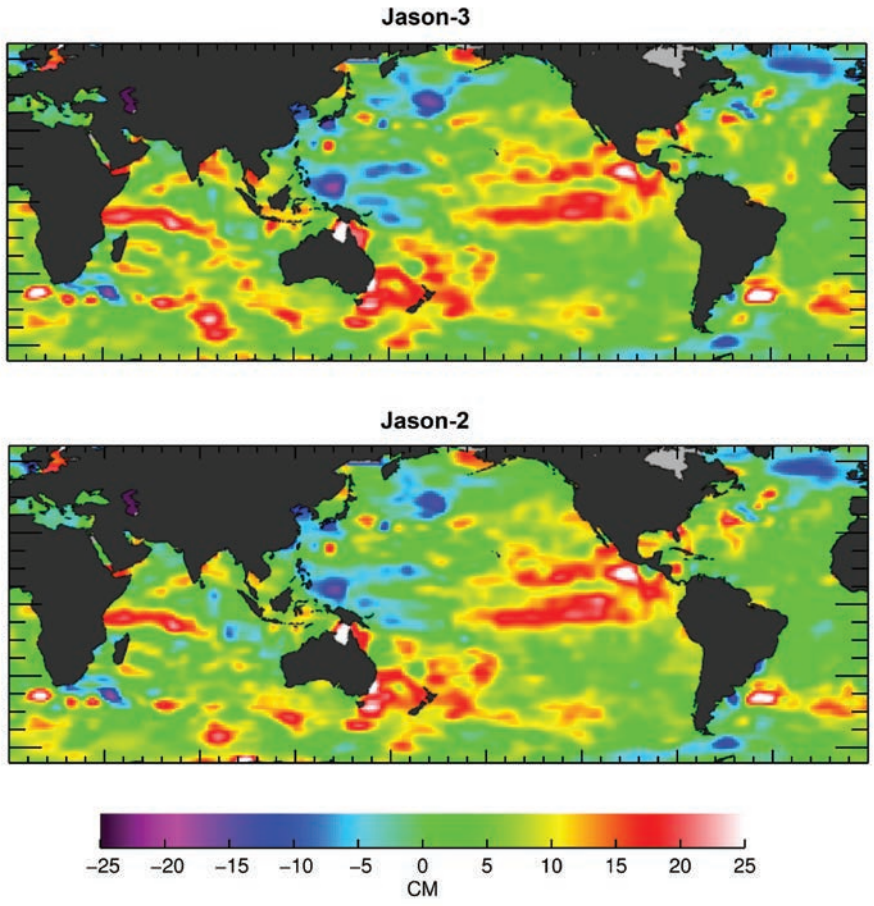
(COSMIC) constellation, which provides precision radio occultation (RO) soundings to support improved NWP model forecasts. The project is a partnership between the National Space Organization (NSPO) of Taiwan and the United States. Over its lifetime, COSMIC has proven to be an extremely cost-effective 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 under the May 27, 2010, agreement 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. The first six of 12 satellites are planned for launch no earlier than September 15, 2017, into an equatorial orbit. The second set is planned to be launched into a polar orbit about three years later.

NOAA's Ocean Altimetry Satellite

NOAA, in partnership with NASA, Centre National d'Études Spatiales (CNES), and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), operates Jason-2, a sea surface topography mission that flies an altimeter to provide high-precision measurements of sea surface height. Jason-2 has been crucial to improvements in weather modeling and tropical storm intensification forecasting because the temperature of the ocean and its currents can change the height of the sea, which can affect the world's weather, including tropical storms. Jason-3, launched in January 2016, continues NOAA's ocean altimetry mission. Jason-3 reached its final orbit and travels one minute and 20 seconds behind Jason-2. These satellites are flying in tandem formation in order to calibrate and validate Jason-3's data. Jason-3 was declared NOAA's primary operational spacecraft in 2016.

NOAA's Space Weather Satellites

NOAA, in partnership with NASA and the United States Air Force, celebrated its first year in deep space. Launched in February 2015, the Deep Space Climate



Shown here are sea-level anomalies from February 12 through 22, 2016, from both the Jason-2 and Jason-3 satellites. This first map of sea surface height from Jason-3 corresponds well to data from its predecessor, Jason-2. Higher-than-normal sea levels are red; lower-than-normal sea levels are blue. El Niño is visible as the red blob in the eastern equatorial Pacific.

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; it also gives 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. Once fully calibrated and validated, DSCOVR succeeded NASA's Advanced Composition Explorer's (ACE) role in supporting solar wind alerts and warnings from the Lagrange point 1 (L1) orbit, the neutral gravity point between Earth and the sun

approximately one million miles from Earth. DSCOVR was declared the primary operational spacecraft in 2016.

NOAA's 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 (COSPAS-SARSAT) system 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. The system has rescued over 39,000 people worldwide since 1982. NOAA provides space on its polar-orbiting satellites for the French processor and Canadian receiver.

Another capability lies in the Advanced Microwave Scanning Radiometer 2 (AMSR2). The AMSR2 on board the Global Change Observation Mission–Water (GCOM-W1) satellite is a remote sensing instrument for measuring weak microwave emission from the surface and atmosphere of Earth. From about 435 miles (700 kilometers) above Earth, AMSR2 provides us with highly accurate measurements of the intensity of microwave emission and scattering. AMSR2's antenna rotates once per 1.5 seconds and obtains data over a 901-mile (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

NOAA and EUMETSAT signed a major agreement in December 2015 to continue to share the responsibility of operating polar-orbiting weather satellites for the next 20 years. Under the Joint Polar System Agreement, NOAA and EUMETSAT will continue to split responsibility for and share data from the two primary polar orbits: EUMETSAT satellites will cover the midmorning orbit, while NOAA will

be responsible for the afternoon orbit. The agreement covers NOAA's planned JPSS-2, -3, and -4 satellites and EUMETSAT's second-generation Metop satellites, ensuring that the United States, Europe, and the world will have the data required for modern weather forecasting through the late 2030s. The agreement builds on existing cooperation with the first-generation EUMETSAT Metop satellites, as well as NOAA POES, Suomi NPP, and JPSS-1 satellites.

On October 16, 2015, the United States signed a cooperative arrangement with the European Union that will give the United States secure, near-real-time access to data from Europe's Sentinel series of Earth observation satellites. The signing of the current bilateral arrangement formalizes the collaboration between NASA, NOAA, the United States Geological Survey (USGS), EUMETSAT, and the European Space Agency (ESA) to realize the full value of these Earth observation satellites for research and operational purposes.

Based on a high-level statement of joint intent, the Japan Aerospace Exploration Agency (JAXA) and NOAA are planning to develop a successor sensor for the Advanced Microwave Scanning Radiometer 2 (AMSR2) on the Global Change Observation Mission–Water (GCOM-W) to avoid a gap in the availability of data required for global weather forecasting. JAXA is beginning research on the sensor in the next year.

National Institute of Standards and Technology

In FY 2016, the National Institute of Standards and Technology (NIST) continued to provide 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. These wide-ranging NIST outputs are grouped into four main categories: 1) measurements to support aerospace manufacturing, 2) measurements to support the aerospace industry and space exploration, 3) technology developments to support the aerospace industry and space exploration, and 4) calibrations of satellite sensors.

NIST Measurements to Support Aerospace Manufacturing

In FY 2016, 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, Spirit Aerospace, and others in addressing the measurement needs of aerospace manufacturing companies. To meet these needs, NIST

- identified technical issues and requirements definitions for industrial wireless networking, cybersecurity in manufacturing environments, and prognostics for manufacturing systems;
- engaged with the FAA, DOD, and NASA to identify proposed approaches for qualification and certification of additive manufacturing materials, processes, and parts;
- collaborated with members of the Additive Manufacturing Consortium (AMC) to conduct round-robin testing and determine the mechanical properties of Inconel 625 parts;
- discussed technology advancements and new standards relevant to aircraft manufacturing and sustainment at the 2016 Aircraft Airworthiness and Sustainment (AA&S) Conference; and
- performed measurements to enable new capabilities for collaborative robotics.

In the first three quarters of FY 2016, the NIST Manufacturing Extension Partnership (MEP) engaged in 189 projects with 113 individual manufacturing companies designated with an aerospace North American Industry Classification System number (NAICS 3364). The MEP post-project followup survey of aerospace NAICS companies revealed that MEP services resulted in the creation or retention of 5,895 aerospace jobs, over $133 million in new sales, nearly $193 million in retained sales, over $147 million in new investment, and $126 million in cost savings.

NIST Measurements to Support the Aerospace Industry and Space Exploration

In FY 2016, NIST supported the aerospace industry and relevant Government agencies across various programs by providing measurements, calibration services, and research traceable to international standards, where NIST

- worked with DOD and Boeing to develop calibration methodologies and facilities for laser-scanner systems used for the accurate dimensional measurements of aircraft components;
- provided air-speed measurement calibrations of anemometers used at airports, on aircraft, and in wind tunnels;
- prepared a new release of the online NIST Atomic Spectra Database, used by astrophysicists and astronomers for the calibration of equipment searching for exoplanets;
- utilized the NIST Van de Graaff accelerator with SolAero Technologies Corporation to "space qualify" solar cells by irradiating them with the equivalent number of electrons that the cells would experience in several decades of Earth orbit; NIST and NASA Goddard Space Flight Center (GSFC) also used high-energy electron beam radiation to test components destined for the Interstellar Mapping Probe (IMAP), Europa Deep Geophysical Explorer (EDGE), and Europa Clipper missions;
- used the M48 Coordinate Measuring Machine (CMM) to accurately measure composite alignment mounts for the Primary Mirror Backplane Support Structure (PMBSS)—the largest single structure on the James Webb Space Telescope (JWST); and
- continued to support NASA in the development of its MaterialsLab microgravity materials science program for materials experiments aboard the International Space Station (ISS); for more information, see *https://www.nasa.gov/mission_pages/station/research/news/materialslab.*

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 unique NIST neutron facility resources to perform measurements on several aerospace-related systems, including metal heat pipes that cool the leading edge of

and high-powered electronics within hypersonic aircraft, ISS spacesuit relief valves, cryogenic liquid propellants critical for understanding long-term microgravity storage of cryogens, proton-exchange membrane fuel cells, and aluminum alloys originated during supersonic particle deposition.

NIST Technology Developments to Support the Aerospace Industry and Space Exploration

In FY 2016, NIST collaborated with NASA and NASA-related entities such as GSFC; the Jet Propulsion Laboratory (JPL); the Space Science Laboratory; and Sensor Sciences, LLC, on a diverse set of projects for developing detectors used in space applications. To reach project goals, NIST

- designed and fabricated nanotextured gallium nitride (GaN) and GaN nanowires to serve as raw materials for photocathode-based detectors;
- created superconducting nanowire single-photon detectors (SNSPDs), including small arrays of this detector technology;
- generated superconducting transition-edge sensor (TES) polarimeters to provide the most-sensitive measurements of cosmic microwave background (CMB) polarization to date and for incorporation into the balloon-borne instrument SPIDER;
- fabricated NIST-developed Microwave Kinetic Inductance Detectors (MKIDs) to measure electromagnetic signals from millimeter waves to x-rays and for deployment in the Balloon-borne Large-Aperture Submillimeter Telescope–The Next Generation (BLAST-TNG);
- disseminated Superconducting Quantum Interference Devices (SQUIDs) and SQUID-based multiplexers to multiple researchers and used the related detector expertise to develop magnetic micro-calorimeters; and
- developed precision microchannel plate detectors using novel cross-strip anode readouts, relevant for neutron imaging and in x-ray telescopes that peer into space.

Also in FY 2016, NIST supported ESA's Atomic Clock Ensemble in Space (ACES) and Space Optical Clock (SOC) programs by continuing preparations to

host a Microwave Link Ground Terminal and participating in microwave link time and frequency transfers.

NIST worked with NASA GSFC by using NIST-developed infrared interferometry methods to characterize and certify critical imaging parts of NASA's WFIRST space telescope, which was designed to investigate the distribution and evolution of dark energy and dark matter in the universe.

NIST collaborated with the University of Texas at Austin on a NASA-funded project to improve the performance of immersed silicon diffraction gratings for a new generation of compact satellite-based spectrometers used in the analysis of remote stars, interstellar gases, and extrasolar planets.

NIST partnered with the University of Colorado Laboratory for Atmospheric and Space Physics (LASP) and NASA to develop and fabricate a Carbon Nanotube Electrical Substitution Radiometer (CNT ESR) for the Compact Solar Irradiance Monitor (CSIM) instrument.

NIST Calibrations of Satellite Sensors

In FY 2016, NIST continued to provide calibration measurements, services, and support for multiple space-related programs. The satellite systems relied on unique measurement expertise, where NIST

- provided calibration support for sensors within the satellite missions JPSS and Geostationary Operational Environmental Satellite-R Series (GOES-R), with NIST transferring its calibration technology to NASA GSFC and LASP;
- utilized the NIST Synchrotron Ultraviolet Radiation Facility (SURF) III to support the calibration of the Extreme Ultraviolet (EUV) Variability Experiment (EVE) aboard NASA's Solar Dynamics Observatory (SDO); 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;
- performed measurements of the amount of light from the moon and sun to enable the moon to serve as a calibration source for satellite sensors while in Earth orbit;

- calibrated the Marine Optical Buoy (MOBY), which is in turn used in the calibration of satellite sensors for ocean-color measurements, and worked with NOAA to improve measurement variability and uncertainty as part of the MOBY Refresh effort;
- utilized the NIST-developed Missile Defense Transfer Radiometer (MDXR) to perform calibrations for infrared remote sensors used by the Missile Defense Agency;
- calibrated optical apertures for the NASA Total and Spectral Solar Irradiance Sensor (TSIS), which is used aboard the ISS to measure solar power per unit area that reaches Earth; and
- continued to develop versions of the NIST Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources (SIRCUS) facility, which provides tunable, powerful, and uniform irradiance to calibrate satellite sensors, with both NASA GSFC and LASP.

International Trade Administration

Industry and Trade Policy

The Office of Transportation and Machinery (OTM) pursued multiple paths to promote exports of products and services that will support the Next Generation Air Transportation System. OTM created and published an online NextGen Solutions Vendors Guide to help foreign customers identify U.S. companies that can provide products that meet the requirements of the International Civil Aviation Organization's (ICAO) Aviation System Block Upgrade (ASBU) technology roadmaps. OTM participated in the World Air Traffic Management Congress in Madrid, Spain, to cohost (with the Aerospace Industries Association) a networking reception for foreign air navigation device providers to meet with industry and hear from the senior Federal Aviation Administration leadership. OTM also took the opportunity to learn about the specific air-navigation procurement needs of specific countries, counsel individual companies on NextGen-related prospects, and recruit participants for the NextGen Solutions Vendors Guide while at the Congress. OTM also participated in a number of domestic conferences and

exhibitions (such as the 58th Air Traffic Control Association Conference and Exhibition and the 2014 Air Transportation Information Exchange Conference) to discuss the future of the NextGen market with individual companies.

Additionally, OTM worked with the FAA, the Transportation Security Administration (TSA), and the State Department in preparation for the 39th ICAO Assembly in September 2014, providing the International Trade Administration (ITA) perspective on aviation safety, aviation security, air-navigation policy and procurement, and the economics of air transportation. ICAO formally endorsed the ASBU roadmaps at the Assembly.

OTM also participated in the Unmanned Aircraft Systems (UAS) Symposium and the Association for Unmanned Vehicle Systems International (AUVSI) Unmanned Systems Conference to engage with Government, academic, and industry stakeholders within the UAS community, to learn more about the projected market for UAS, to hear about the latest roadmaps for the technology, and to recruit participants for the NextGen Solutions Vendors Guide (particularly the section on Remotely Piloted Aircraft). Specifically, OTM cultivated contacts with various state business development offices at Unmanned Systems 2016, with particular emphasis on the regions represented in the FAA's six UAS test sites.

OTM renewed a Memorandum of Agreement (MOA) with Embry-Riddle Aeronautical University (ERAU) to share data and aerospace information and to promote the competitiveness, sustainability, and innovation of the U.S. aerospace manufacturing industry. The renewed MOA includes an addendum detailing a new virtual research partnership program in which ERAU-Worldwide students will research topics suggested by ITA.

Throughout the year, OTM organized and led four meetings of the Industry Trade Advisory Committee for Aerospace Equipment (ITAC 1). The committee provides advice to the Secretary of Commerce and the U.S. Trade Representative on aerospace-related trade policy issues.

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 has provided support for the ongoing U.S.–European Union (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. A new ASU, which had been completed in early 2011, went into full effect in 2013, and its effects were still being observed in 2016. As a member of the U.S. delegation, ITA helped ensure that the interests of industry were addressed as the new ASU was implemented and monitored and provided advice on how Ex-Im Bank programs affect the aerospace industry.

ITA and NOAA continued their active participation in the implementation of the current National Space Policies, which include industrial base and competitiveness issues. ITA's OTM actively participated in the implementation of several actions that were identified in the June 2010 National Space Policy, which revised and updated several aspects of the previous policies. In order to ensure that commercial interests continue to be adequately addressed, OTM and NOAA continued to ensure that all of the policies' implementation actions would improve U.S. industry's competitiveness, stimulate the American economy, increase exports, and create U.S. jobs.

OTM continues to represent commercial remote sensing satellite industry interests within the Remote Sensing Interagency Working Group (RSIWG), led by the State Department. The RSIWG coordinates policy for the export of commercial remote sensing satellite systems and negotiates government-to-government agreements that address the safeguarding of those systems' technology. The RSIWG consulted with several foreign countries on satellite cooperation and met with industry representatives to understand the impact on related businesses.

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 and helicopters, airport construction, communications, remote sensing satellites, commercial projects, and air traffic management projects.

Industry and Trade Promotion

In July 2016, ITA organized and supported the Commerce Department's participation in the Farnborough International Air Show and arranged senior-level meetings for the Secretary of Commerce and the Assistant Secretary for Industry and Analysis 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.

ITA's Global Aerospace and Defense Team recorded approximately 204 Written Impact Narratives (WINs) in FY 2016. A WIN is a new organizational metric that showcases ITA's contribution to a company's success. These include Commercial Service (CS) personnel–impacted deals with small- and medium-sized companies, as well as with larger corporations such as Bell Helicopter, Boeing, General Dynamics, Lockheed Martin, and United Technologies Corporation.

The Global Team held over 800 counseling sessions with 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 International Air Show, the Seoul Airshow, the Singapore Airshow, Feria Internacional del Aire y del Espacio (FIDAE, South America), and the Africa Aerospace and Defense Summit, among others.

Bureau of Industry and Security

The Bureau of Industry and Security (BIS) continued to support the President's Export Control Reform efforts as they relate to spacecraft. During this fiscal year, BIS worked with industry and the interagency Space Working Group on identifying changes to the current regulations on spacecraft and related items. The changes under discussion include updates to the remote sensing controls and other areas identified by industry. BIS expects to publish changes in these areas in the first quarter of FY 2017. Feedback from industry continues to be very positive. BIS participated in the Commercial Satellite Technical Advisory Committee International Space Policy Working Group and added some space expertise to its Transportation Technical Advisory Committee.

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. The entire Landsat archive became available for download at no charge in December 2008, and by the end of September 2015, more than 29 million Landsat scenes had been downloaded by the user community. In addition to distributing aerial photography through the National Map, the USGS archived and distributed 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; U.S. and global ecosystem health monitoring; land-use change; emergency response; and assessments of natural hazards such as fires, hurricanes, earthquakes, droughts, and floods.

Assessing Vulnerability to Drought in Dryland Ecosystems

Scientists at the USGS Southwest Biological Science Center are partnering with the USGS Western Geographic Science Center, the USGS Earth Resources Observation and Science Center, and the University of Arizona to help managers plan for and manage drought-impacted ecosystems in the western United States by conducting research that synthesizes plot-based and remotely sensed vegetation-monitoring data. Analyses using a time series of Moderate Resolution Imaging Spectroradiometer (MODIS)– and Landsat-derived vegetation indices reveal the importance of critical climate windows and pivot points that drive vegetation condition across ecoregions of the western United States. The team is working to understand how landscape and soil attributes, in combination with management actions, mediate climate-vegetation relationships and the balance between grasses and woody plants, which has important implications for ecosystem function. The team is building short-term forecasts of vegetation condition using multi-model ensembles of climate and water balance variables that can help managers make short-term decisions and plan for long-term changes in vegetation composition and distribution. More information can be found at *https://nccwsc.usgs.gov/display-project/5050cb0ee4b0be20bb30eac0/551ad102e4b03238427837ba*.

Green-Up and Evapotranspiration of the Colorado River Delta

During the spring of 2014, 130 million cubic meters of water was released from Morelos Dam on the lower Colorado River, allowing water to reach the Gulf of California for the first time in 13 years. Nearly two years later, scientists continue to analyze the effects of this historic experiment—the result of a new agreement between the United States and Mexico. To assess the response of vegetation to the pulse flows, remote sensing techniques were used to measure green-up and evapotranspiration (ET) of vegetation within the delta's riparian corridor. ET was assessed with an algorithm derived from MODIS Enhanced Vegetation Index (EVI) data, while green-up was measured using Landsat 8 Normalized Difference Vegetation Index (NDVI) data. There was a small but significant increase (three percent) in ET and a significant increase (17 percent) in NDVI from 2013 (pre-pulse) to 2014

(post-pulse) within the delta's riparian corridor ($P < 0.05$). While NDVI declined in 2015, it was still significantly higher than in 2013 ($P < 0.05$). This increase reverses an overall decline in NDVI and ET since the last major flood in 2000. Using the ET findings coupled with salinity data collected during the pulse flows, USGS researchers developed a conceptual model explaining the role of groundwater and surface flows in maintaining the riparian corridor in Mexico. Based on preliminary findings, pulse flows could be an effective tool for restoring the lower Colorado River's riparian zone.

Hindcasting Turbidity in Lake Clark National Park

National Park Service (NPS) water-clarity data were recently combined with Landsat remote sensing data to hindcast turbidity trends in Lake Clark for a 30-year time period (1985–2014). Lake Clark is a glacially influenced nursery lake for sockeye salmon, located in the headwaters of Bristol Bay, Alaska, the most productive wild salmon fishery in the world. Water clarity is a key water-quality property in salmon-bearing lakes. Decreases in water clarity due to increases in glacial runoff have been shown to reduce salmon production by lowering the abundance of prey such as zooplankton. Anecdotal accounts suggest that Lake Clark water clarity is decreasing over time, but no long-term measurements exist to substantiate these observations.

This study addressed that data gap by reconstructing long-term, lakewide water clarity for Lake Clark using the Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) surface reflectance products and in situ water-clarity data. No significant change was detected in the mean annual turbidity of Lake Clark for the time period examined. However, a significant positive trend in May turbidity was found between 2000 and 2014, which could represent an advance in the timing of initial sediment input to the lake via glacial meltwater runoff.

This study demonstrates the utility of hindcasting turbidity in a glacially influenced lake using the Landsat surface reflectance products. It may also provide a framework for reconstructing turbidity records in lakes that lack in situ observations, and it can be a starting point for predicting future water-clarity conditions based on projected climate scenarios. More information can be found at *http://www.mdpi.com/2072-4292/7/10/13692*.

Land Change Monitoring, Assessment, and Projection

The USGS Land Change Monitoring, Assessment, and Projection (LCMAP) initiative centers on structured, operational, ongoing, and timely collection and delivery of accurate and relevant information and knowledge on land use, cover, and condition. LCMAP supports a wide array of objectives: 1) provide documentation and understanding of historical land change and contemporary land change as it occurs; 2) explain how past, present, and future land change affects society, natural systems, and the functioning of the planet at local to global scales; 3) alert relevant stakeholders to important or emerging land-change events in their jurisdictions; and 4) support others in the use of land-change information and science results.

During the past year, significant progress has been made in implementing the first objective. The assembly of an "analysis-ready" Landsat archive that will provide data cubes of Landsat 4–8 surface reflectance and top-of-atmosphere reflectance data for the United States is under way; these data contain pixel-level quality assurance information to enable the screening of clouds and cloud shadows. In addition, prototype 1985–2015 annual land-cover and land-cover-change datasets have been completed for a large portion of the Pacific Northwest and another 10 sites around the country. By late 2017, LCMAP capabilities will include a routine continuous U.S. land-change monitoring capability that is supported by analysis-ready Landsat data, all feeding an agile capacity to provide timely land-change data and assessments for decision makers. LCMAP initially will be implemented for the United States but can be expanded to provide global coverage.

Lidar Assessment of the Black Forest Wildfire

Prolonged drought and climate change continue to increase the prevalence and severity of wildland fire, while the growing number of houses set within natural areas around urban developments (i.e., within the wildland urban interface [WUI]) adds to the potential hazard exposure. Characterizing the risk to WUI housing from wildfire is an important area of natural hazards and applied remote sensing research. This project is investigating how lidar data can be used to describe the

vertical structure and fine-scale fuel characteristics within the home ignition zone. Using the Black Forest Fire of 2013 near Colorado Springs, Colorado, this research is generating lidar-derived vegetation measures, structure characteristics, and landscape features to quantify the prefire conditions that increased or decreased the likelihood of structure ignition and consumption in the state's most destructive wildfire event to date. In addition to addressing this disaster, answers derived from these methods are useful for informing hazard-mitigation decisions across the growing wildland urban interface in the western United States. More information can be found at *http://geography.wr.usgs.gov/science/fire/*.

Mapping When and Where Invasive Buffelgrass Is Green

Buffelgrass is a perennial grass that is invasive to the Sonoran Desert of the Southwest, where it threatens desert ecosystems by out-competing native plants and altering fire regimes, with the potential to transform the Sonoran Desert ecosystem from a diverse assemblage of plants to a grassland monoculture. The USGS has developed a new and innovative suite of landscape metrics (i.e., "Climate-Landscape Response" or CLaRe metrics) that are proven effective in mapping when and where invasive buffelgrass is green in Saguaro National Park (SNP) near Tucson, Arizona. CLaRe phenometrics, derived from gridded climate data and 250-meter MODIS data, capture the strength of the landscape greenness response to climate and expose buffelgrass due to its rapid and strong response to recent precipitation. Buffelgrass remains dormant much of the year but has short windows when it is photosynthetically active and vulnerable to herbicide. By mapping when and where buffelgrass is green, land managers can optimize their treatment activities, saving money. In addition, current results suggest that it is possible to detect nascent populations of buffelgrass covering less than five percent of the landscape by monitoring the trends of these CLaRe phenometrics. More information can be found at *http://www.mdpi.com/2072-4292/8/7/524*.

Modeling Landscape-Scale Habitat Relations for Landbirds During Migration

Millions of landbirds migrate through the Gulf of Mexico region each spring and autumn. Migration is taxing, and these migrants depend on stopover habitats to provide the food and cover needed to complete their journeys. For some species, as much as 85 percent of annual mortality occurs during migration. Stopover habitats in the Gulf of Mexico region have been lost or degraded due to the effects of development, agriculture, livestock grazing, timber industry activities, and the spread of exotic species. The continued loss or degradation of stopover habitat poses a risk to migrating birds, so knowing the location and landscape composition where peak numbers of birds consistently stop to rest and forage is critical for conservation planning. USGS Wetland and Aquatic Research Center scientists are using weather surveillance radar data and landscape metrics to model bird-habitat relations within 43 miles (70 kilometers) of four radar stations along the western coast of the Gulf of Mexico. Reflectivity data collected from 2008 to 2012 were used to estimate migratory landbird density during spring and fall migration. Landscape variables were measured from 2006 Coastal Change Analysis Program (C-CAP) land cover, National Elevation National Hydrography, and 2010 U.S. Census Bureau Topologically Integrated Geographic Encoding and Referencing (TIGER) datasets. Results of this research will support the conservation plans of the Gulf Coast Joint Venture by identifying the factors that characterize suitable migratory landbird stopover habitat.

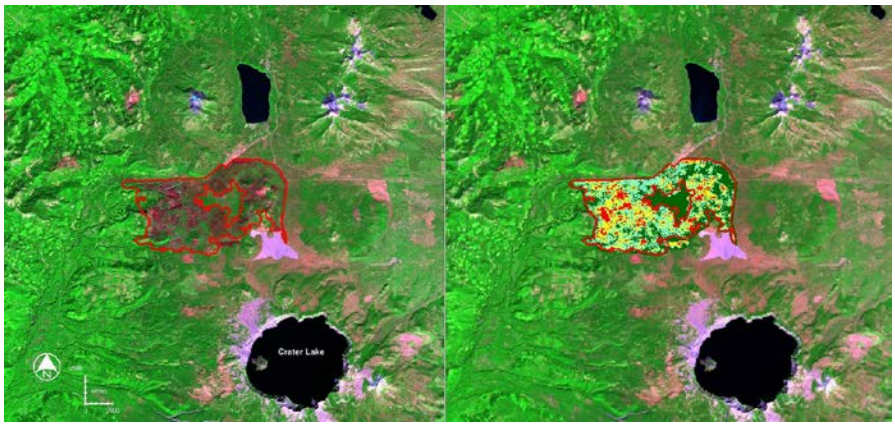
Remote Sensing Support for Burned Area Emergency Response Teams

Since 2003, the USGS Earth Resources Observation and Science (EROS) Center and the U.S. Forest Service (USFS) Remote Sensing Applications Center (RSAC) have jointly provided satellite-derived burn severity mapping products to meet the requirements of DOI and USFS Burn Area Emergency Response (BAER) teams. BAER teams are mandated to quickly (within two weeks) evaluate the effects of wildland fires and develop mitigation plans to safeguard valuable natural resources, protect human life and property, and promote landscape recovery. Derived from Landsat images, the soil burn severity map is a major resource used by

the BAER teams to develop postfire hazard-mitigation prescriptions. Additionally, burn severity maps are provided to USGS Landslide Hazards staff to support ongoing debris flow modeling and prediction analyses associated with wildland fires.

The USGS EROS Center rapidly processes Landsat and other satellite imagery enabling the timely generation of map products for large wildland fires on DOI-managed lands, generally less than two days after fire containment. These map products allow the BAER teams to better understand the patterns of burn severity and make more precise mitigation recommendations. Since 2003 and through the 2015 fire season, the USGS and USFS have mapped 1,594 wildfires representing 46.7 million burned acres in support of BAER and local DOI and USFS land managers.

In 2016, wildland fire activity on DOI-managed lands was extensive. By early June, the USGS had responded to five DOI requests for burn area mapping support. Additionally, USGS assistance was requested by the Provincial Operations Centre in Edmonton, Alberta, Canada, to help with the acquisition of Landsat and other satellite imagery for the wildfire near Fort McMurray that covered over one million acres.



This composite image shows a Landsat postfire image (September 20, 2015; left) and preliminary soil burn severity map superimposed on a Landsat prefire image (September 1, 2014; right) for the August–September 2015 National Creek Complex fire in Oregon's Crater Lake National Park. The fire burned 16,744 acres just north of Crater Lake and was the largest in the recorded history of the park. Within the postfire image, the burn scar is medium to bright red, while vegetation appears in various shades of green. Within the burn severity map, dark green indicates non-burn, light blue indicates low severity, yellow indicates moderate severity, and red indicates high severity. The approximate burn perimeter is designated by a red polygon in both images.

Satellite-Based Water Use Mapping

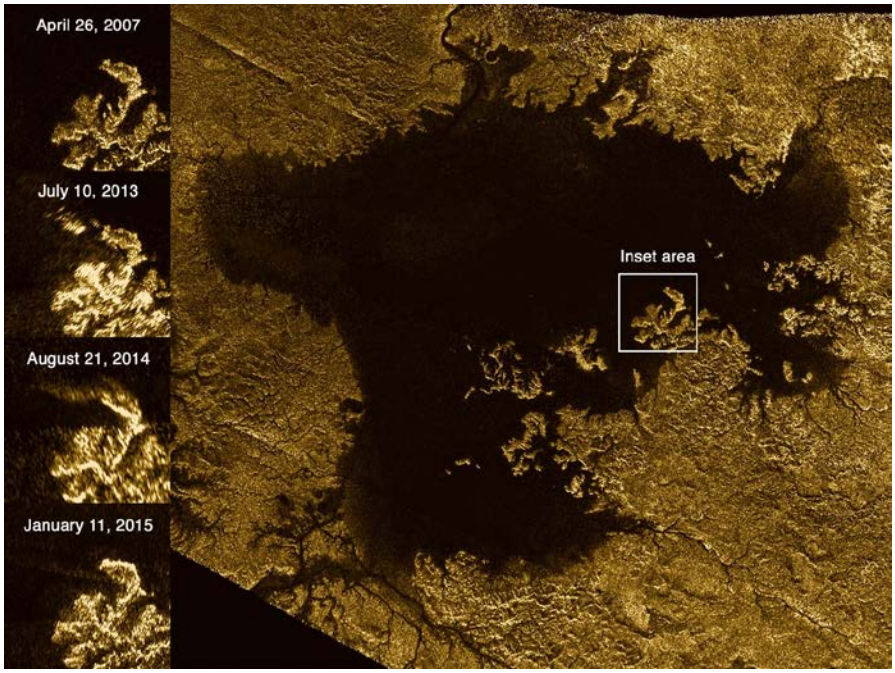
The USGS is applying satellite remote sensing resources and expertise to quantify evapotranspiration for the National Water Census and the Sustain and Manage America's Resources for Tomorrow (WaterSMART) initiative. Work developed at the USGS EROS is focused on understanding and quantifying the spatial and temporal distribution of water consumption, i.e., water that is used by the soil and vegetation complex and returned to the atmosphere in the form of evaporation and transpiration, which makes it unavailable for other uses. The USGS works collaboratively with stakeholders to enable powerful technical capabilities within a geographical context by targeting efforts in watersheds or basin-level Focus Area Studies, where the resulting tools and information can soon become the basis for monitoring and assessing water use across the Nation.

Changes in climate, land use, and water demand are placing increased pressure on the Upper Rio Grande Basin's (URGB) limited water resources, necessitating careful water management decisions. Accordingly, in collaboration and coordination with the USGS New Mexico Water Science Center, maps of estimated water use were created for the 2015 growing season in the URGB using freely available Landsat thermal (infrared) imagery and weather data. These water use maps are being validated with data from 2007 to 2014; once they are validated, they can be applied going forward. By planning today for water tomorrow, this work helps to ensure that the research is timely and relevant in a regional and national context.

Determining remotely sensed ET and agricultural consumptive use from Landsat allows for temporal evaluation with a critical spatial component to see trends at the level of individual fields and across entire landscapes. Water use maps can allow insight into crop-specific productivity, drought implications, and water budget analyses, which can include surface and groundwater, along with environmental flow. The USGS EROS develops and shares these ET products with USGS Water Science Centers that are responsible for compiling water use data every five years. Similarly, researchers at the North Central Climate Center and the Bureau of Reclamation are evaluating these products for their usefulness for continual scientific analyses and agro-hydrologic modeling. More information can be found at *http://water.usgs.gov/watercensus*.

Saturn's Moon Titan—A Last Look with Cassini

USGS scientists have been involved in mission planning, cartographic data processing, and scientific studies for the international Cassini-Huygens mission to the Saturnian system since its inception in the early 1990s. Saturn's Mercury-sized moon Titan, which has a range of geological features and processes unmatched by any other body besides Earth, has been the main focus of these efforts. With a little over a year left before the spacecraft is deliberately flown into Saturn's atmosphere to burn up, the mission is embarking on a "Grand Finale" that will bring its nearest orbit around Saturn to just outside the ring system and then into the narrow gap between the rings and the planet's cloud tops. These final orbits will provide unprecedented detailed views of Saturn's rings and atmosphere as well as measurements of the gravitational and magnetic fields. They will also provide the last looks at Titan with multiple instruments, including a final peek at the "magic island" in



In this Cassini synthetic aperture radar image of the north pole of Saturn's moon Titan, the dark feature is Ligeia Mare, a 248-mile (400-kilometer)-wide sea of liquid hydrocarbons. The inset shows the so-called "magic island," which appeared in 2013 and then vanished again. A variety of explanations for the transient feature have been considered, but the most likely is that it was a "glint" off a patch of waves on the sea surface caused by local winds.

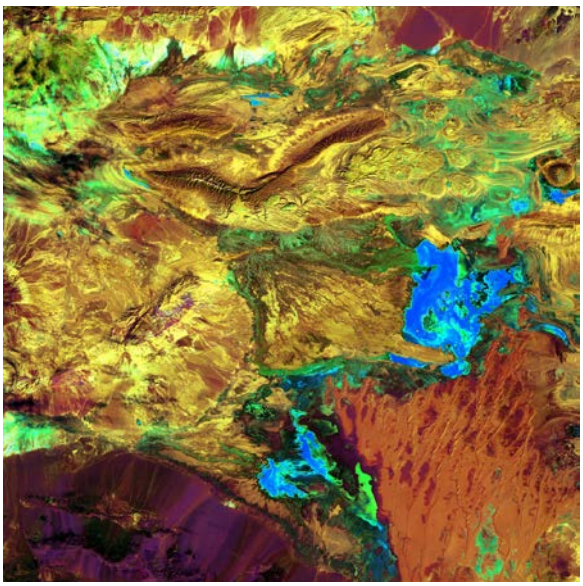
the north polar hydrocarbon sea Ligeia Mare, which has been visible only intermittently in previous observations.

Space-Based Tracking of Inundated Area Dynamics

The Dynamic Surface Water Extent (DSWE) product under development at the USGS can be used to systematically characterize cycles and changes in surface inundation for a broad variety of applications. DSWE presents the results of tests for the presence of open water and mixtures of surface water and vegetation in Landsat Thematic Mapper, Enhanced Thematic Mapper Plus, and Operational Land Imager (OLI) image pixels collected over the United States. As one regional-scale example, DSWE data from 1984 through 2015 were used to calculate the yearly proportion of pixels free of clouds, cloud shadows, and snow that are classified as "open water" for the entire Chesapeake Bay Watershed (CBW). These proportions resulted in a time series of CBW areas that were consistently inundated on an annual basis. Such data can in turn be summarized over smaller areas such as watersheds or counties. A county-level assessment of changes between 1985 and 2015 in the CBW identified Sussex County, Delaware, as having a relatively large increase in perennially inundated area. A semi-decadal subset of these maps shows the consistent trend toward greater perennially open water in the area of the Prime Hook National Wildlife Refuge. Restoration efforts are currently under way to reverse this trend; the derivation of DSWE data from Landsat images collected in the future will hopefully show decreases in open water as those areas are replaced by improved habitat (i.e., water/vegetation mixtures). Research is under way to increase DSWE thematic accuracy and temporal resolution by combining Landsat scenes with other remotely sensed images and in situ monitoring data. For the end user, the DSWE product will provide a cost-effective, temporally consistent means of assessing inundation dynamics over intra- and inter-annual periods not only for habitat and water resource management, but for climate and land-use change science and forecasting. This work is supported by the USGS Land Remote Sensing and Land Change Science Programs. More information can be found at *http://remotesensing.usgs.gov/ecv/SWE_overview.php.*

Users, Uses, and Value of Landsat Imagery

Landsat data are an invaluable resource of moderate-resolution satellite imagery available to the public for free through the USGS. These data, available from 1972 through the present, have been used in countless studies, including monitoring land-use change, deforestation, glacier recession, sea ice extent, invasive species, and population growth. To help assess the uses and value of Landsat imagery, social scientists at the USGS Social and Economic Analysis (SEA) Branch of the Fort Collins Science Center in Colorado are leading a long-term study, which includes surveys and case studies of Landsat imagery users. A series of surveys provides longitudinal data on how the users and uses of the imagery are changing over time in response to changes in the provision of the imagery, which include the shift to online access (including the development of the full-resolution browser function), the no-cost downloading policy, and the launch and decommission of different Landsat satellites. The results allow analysts to explore the value of the imagery. Multiple case studies that focus on the use and benefits of Landsat imagery in water, agriculture, forestry, and private-sector technological applications provide context and depth to complement the more quantitative survey data. In 2016, a report on the results of the most recent 2014 survey of Landsat users was published and can be found at *https://pubs.usgs.gov/of/2016/1032/ofr20161032.pdf.* Additional analysis of the 2014 survey data, as well as 2015 user data from the USGS Earth Resources Observation and Science (EROS) Center, was completed to help inform



This "Earth as Art" Landsat image shows the Great Salt Desert in Iran.

the collection of Landsat 10 requirements. The Landsat Study can be accessed at *https://www.fort.usgs.gov/landsat-study*.

Using Repeat Airborne Lidar and Landsat to Quantify Arctic Tundra Fire Impacts

Wildfire disturbance is an important factor contributing to ecosystem and landscape changes. The impact of fires on permafrost-influenced terrain in boreal forest regions is well-documented; however, the role of fires in initiating thermokarst development in arctic tundra regions is poorly understood. Rapid climate change at high latitudes has increased interest in the spatial and temporal dynamics of thermokarst and other permafrost thaw-related features in diverse disciplines including landscape ecology, hydrology, engineering, and biogeochemistry. As a result, there is an urgent need to develop new techniques and tools to observe and quantify changes to near-surface permafrost terrain.

Remote sensing provides a means for documenting and quantifying many of the changes now occurring on arctic landscapes. In particular, the application of multitemporal airborne lidar allows for the detection of terrain subsidence caused by thermokarst. Lidar elevation model differencing provides a direct measure of land-surface elevation changes over time. This study compares two airborne lidar datasets covering approximately 400 square kilometers acquired in the aftermath of the large and severe Anaktuvuk River tundra fire that occurred in 2007 in northern Alaska. Digital terrain models (DTMs) at one-meter spatial resolution were developed from the lidar datasets that were acquired two years and seven years postfire. These datasets were differenced using the Geomorphic Change Detection tool to quantify thermokarst development in response to the tundra fire disturbance.

Results show permafrost thaw subsidence (more than 0.2 meters) occurring across 34 percent of the burned tundra area studied, compared to less than one percent in similar undisturbed, ice-rich tundra terrain. Postfire thermokarst development as detected in the airborne lidar data shows a relationship with trends in a dense time series of different multispectral indices (including Tasseled Cap and NDVI) derived from multispectral Landsat satellite data. These relationships allow

scaled-up mapping of thaw-affected terrain area across the entire ~1,000-square-kilometer area impacted by the Anaktuvuk River tundra fire; where sufficient cloud-free Landsat data are available, they may also allow for the assessment of thermokarst impacts across other tundra fire disturbances since the mid-1980s.

These new methodologies will enable the assessment of the vulnerabilities of ice-rich permafrost terrain to changing disturbance regimes in northern high-latitude landscapes. A better understanding of the processes controlling thermokarst initiation and development in Arctic regions is important because of the resulting impacts on the land-atmosphere exchange of water, energy, and greenhouse gases, along with the influence on surface hydrology, snow accumulation, and vegetation dynamics. More information can be found at *http://www.nature.com/articles/srep15865*.

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

Benefits of Sage Grouse Landscape Protection Strategies for Songbirds, a Rangewide Assessment: Migratory Birds—Intermountain West Joint Venture

FWS researchers investigated whether the recent, unprecedented scale of sage grouse (*Centrocercus urophasianus*) conservation in the American West has had beneficial effects on other sagebrush-obligate species. North American Breeding Bird Survey (BBS) count data and machine learning were used to assess predictors

influencing spatial distribution and abundance of three sagebrush-obligate songbirds: Brewer's sparrow (*Spizella breweri*), sagebrush sparrow (*Artemisiospiza nevadensis*), and sage thrasher (*Oreoscoptes montanus*). Researchers quantified co-occurrence of songbird abundance with sage grouse lek (breeding and nesting site) distributions using point pattern analyses and evaluated the concurrence of songbird abundance within sage grouse habitat restoration and landscape protection.

Sagebrush land-cover predictors were positively associated with the abundance of each songbird species in all models. Individual songbird models identified an apparent 40 percent threshold in sagebrush land cover over which songbird abundances nearly doubled. Songbird abundances were positively associated with sage grouse distributions ($P < 0.01$); rangewide landscapes supporting greater than 50 percent of males on leks also harbored 13–19 percent higher densities of songbirds compared to rangewide mean densities. Additionally, 85 percent of the conifer removal conducted through the Sage Grouse Initiative coincided with high to moderate Brewer's sparrow abundance. The core area of Wyoming's landscapes protected for sage grouse encompasses half of the high- to moderate-abundance sagebrush sparrow and sage thrasher populations. In the Great Basin, half of the high- to moderate-abundance sagebrush sparrow and sage thrasher populations coincides with sage grouse Fire and Invasive Assessment Tool (FIAT) priorities where conservation actions are being focused in an attempt to reduce the threat of wildfire and invasive plants. This work illustrates that spatially targeted actions being implemented ostensibly for sage grouse largely overlap high-abundance centers for three sagebrush-obligate passerines and are likely providing significant conservation benefits for less well-known sagebrush songbirds.

Color Infrared Imagery Informs Wetland Habitat Survey in the Prairie Pothole Region

Each spring since 1987, FWS staff has conducted the Four-Square-Mile Breeding Waterfowl Survey across five states and two FWS regions in the Prairie Pothole Region of the northern Great Plains. Part of the study includes the manual digitization of surface-water extent for approximately 75,000 wetlands on two- by two-mile sample plots to monitor wetland conditions and provide baseline data for modeling

annual waterfowl distribution and abundance. In 2014, Habitat and Population Evaluation Team (HAPET) researchers began integrating new camera systems into the remote sensing protocol to collect submeter color infrared imagery at 380 sample plots. These changes were implemented with the intent of introducing automated water classification algorithms into the workflow to reduce annual effort and increase accuracy.

Using images collected in spring 2015, researchers used eCognition software to produce an automated surface-water classification. Although the classification outputs continue to require some manual interpretation, the average time required to process each remote sensing plot has been reduced approximately 60 percent (from two hours to 45 minutes per plot, or approximately 500 hours less effort per year). With continued enhancement to the classification algorithm, the workload could be reduced further. Additionally, changes were made to the image acquisition protocols that also reduced pilot interaction with the system. Efforts are currently under way to introduce a more robust flight management system (incorporating highly accurate navigational tools and automated camera control) to further reduce the burden on pilots and increase operational safety.

This protocol has also been used to provide input data for studies identifying priority habitat for the rare Wyoming toad (*Anaxyrus baxteri*), provide high-resolution (three-centimeter or ground sample distance [GSD]) orthophotos to inventory three American white pelican nesting colonies (approximately 25,000 individuals), and investigate effects of oil/gas exploration on waterfowl abundance and productivity.

Great Lakes Remote Sensing—Coastal Wetlands

Repeated collection of high-spatial-resolution satellite imagery over the entire Great Lakes coastal zone will allow resource managers to better understand, manage, and preserve the region's dynamic wetland ecosystems. In a binational effort led and funded by the FWS, researchers at Michigan Tech Research Institute, the University of Minnesota, and SharedGeo are collaborating with the Canada Centre for Remote Sensing and with Environment and Climate Change Canada to

produce updated and improved maps of critical coastal wetland characteristics such as surface-water extent, water levels, and vegetation classifications.

This multi-year effort will obtain submeter DigitalGlobe optical imagery via the National Geospatial-Intelligence Agency and RADARSAT-2 radar imagery via the Canadian Space Agency. Optical imagery will be acquired through the National Science Foundation (NSF)–supported Polar Geospatial Center and processed by University of Minnesota personnel. Radar imagery will be processed jointly by the Canada Centre for Mapping and Earth Observation (Natural Resources Canada) and the Wildlife Research and Landscape Science Unit (Environment and Climate Change Canada), in collaboration with the Michigan Tech Research Institute. SharedGeo will provide additional computing and outreach support. Combining information about the physical, chemical, and biological properties of coastal wetlands over space and across time will yield improved coastal wetland habitat information and knowledge. More information can be found at *http://www.tandfonline.com/doi/abs/10.1080/17538947.2011.608813* and *https://www.fws.gov/midwest/es/*.

Lidar Collection in the Outer Coastal Regions of the Yukon and Kuskokwim River Deltas: Science Applications, Western Alaska Landscape Conservation Cooperative

At roughly 50,000 square miles, the Yukon-Kuskokwim River Delta forms a vast, flat expanse in western Alaska that is a critical northern breeding and staging habitat for migrating waterbirds and hosts more than 35 indigenous villages. Due to its orientation, shallow bathymetry, and low relief, the delta is highly vulnerable to coastal flooding associated with storm surges, which can reach miles inland. The region also appears to be subsiding, which further exacerbates flooding concerns. As a result, the villages in the area are some of the most imperiled communities in Alaska. Existing elevation datasets are not adequate for emergency response planning or resource management purposes; high-resolution data are required to accurately map the subtle topography of the delta. In response to the USGS's 3D Elevation Program (3DEP) request for proposals, the Western Alaska Landscape Conservation Cooperative and FWS staff organized a total of six state and Federal agencies to jointly apply for a grant to acquire lidar data over a portion of the

delta. The USGS is contributing additional funding and working with vendors to arrange for lidar acquisition in 2016 and 2017. The intent is to acquire roughly 1,500 square miles of lidar data over some of the most highly productive and vulnerable areas in the delta. The final digital elevation model will have an average accuracy of four to six inches and will be hydro-flattened to allow water bodies to be seen in detail. Lidar data can also be used to assist conservation efforts to establish sustainable summer trails in communities. The project will cover several communities facing substantial climate-change impacts, providing baseline elevation data at a suitable resolution.

Bureau of Land Management

The Bureau of Land Management (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 monitoring data are leveraged to generate information and maps that would otherwise be too expensive to produce. The BLM is developing a core set of integrated and scalable remote sensing tools that will 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.

Forest Vegetation Information System Woodland Inventory—Utah

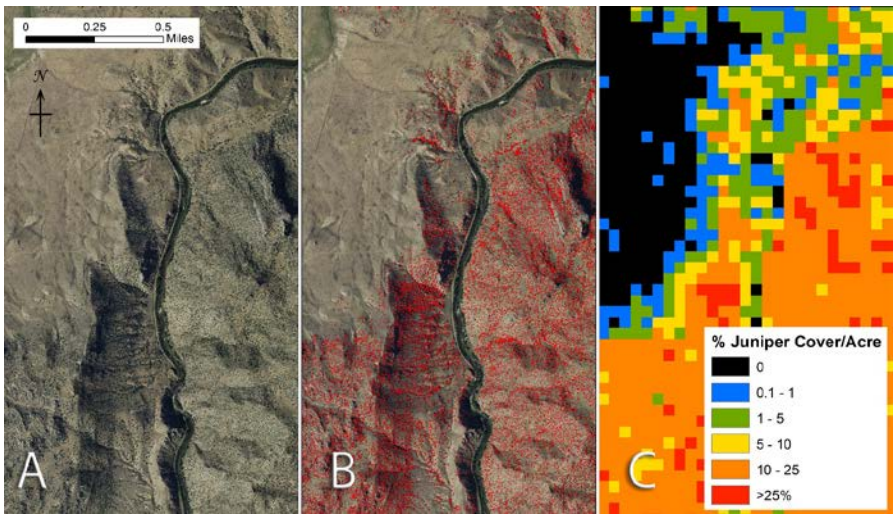
The national-scale BLM Forest Vegetation Information System (FORVIS) provides data about forest attributes and associated land-management activities to inform vegetation inventory and monitoring efforts. Remote sensing technology contributes to this program, facilitating a more efficient and complete inventory of vegetative resources, including non-forested land-cover types such as shrublands and grasslands. This multi-year BLM project will give Utah comprehensive coverage of all vegetative data, making the inventory useful for a wide range of resource applications. For example, one of the inventory project goals in Utah is to identify areas such as pinyon, juniper, and mixed conifer stands that are suitable for biofuel production.

The Cedar City Field Office area has been the starting point for the inventory, which includes 22.9 million acres managed by the BLM in Utah. The process of converting disparate FORVIS data layers into meaningful land-cover information involves the analysis of field and remote sensing data in Trimble eCognition software, which assigns pixels to vegetation categories based on their spectral properties and spatial arrangements. The remote sensing data layers leveraged include one-meter National Agricultural Imagery Program (NAIP) aerial photography, five-meter digital elevation model (DEM) data, and derived slope and aspect products. Field data are collected specifically for this project as well as assembled from multiple additional sources, including existing datasets compiled during other BLM projects, online data portals, and USFS Forest Inventory and Analysis (FIA) data.

Supervised classifications are iteratively performed in eCognition until an acceptable threshold accuracy is reached, at which point the data are entered into the national FORVIS database. Once the Cedar City area is complete, the focus will shift and the program will repeat the process for the Vernal Field Office area. More information can be found at *http://www.blm.gov/nstc/resourcenotes/respdf/RN48.pdf.*

Juniper Expansion Management in the Upper North Platte Watershed

Native woody juniper shrubs (*Juniperus* spp.) are expanding beyond their normal historical ranges as a result of wildfire suppression, prolonged drought, and reduced demand for juniper products such as fencing and building material. As juniper woodlands spread, typically from steep rocky slopes into adjacent foothill riparian and shrub-steppe communities, critical mule deer and greater sage grouse habitat is reduced. Early stages of encroachment can be controlled with cost-effective mechanical treatments, whereas the only economical management strategy for denser canopy cover requires prescribed fire, which is difficult to implement and can lead to increased establishment of invasive grasses. As a result, the BLM Rawlins Field Office actively monitors juniper community expansion to identify early-stage areas suitable for mechanical treatment based on canopy cover and wildlife habitat needs.



Geographic Information System (GIS) products derived from classification of the original 2015 NAIP imagery (image A) included a pixel-level juniper canopy polygon layer (B) and a layer showing juniper canopy cover aggregated by acre unit (C).

BLM analysts used the Feature Analyst extension in Esri ArcMap 10.3.1 to conduct supervised classification of juniper canopy cover from the 2015 four-band, 0.5-meter-resolution NAIP aerial photos acquired over 60,000 acres of BLM-managed rangeland near Saratoga, Wyoming. The study area comprised six separate management units. Representative juniper canopies were used to train the software to recognize the spectral signature and spatial pattern of juniper and classify the imagery for those traits. The river corridor was masked to avoid false positives from willow, alder, and cottonwood. The resulting juniper canopy cover maps provide a simple management tool for determining treatment priorities. For example, the blue and green pixels in the classified image (C) represent low-canopy-cover areas that are suitable for mechanical treatment.

Mine Production Verification Using High-Resolution Stereo Imagery, Royal Gorge Office, Colorado

The BLM uses an array of remote sensing technologies to support resource management. The BLM National Operations Center (NOC) is currently employing unmanned aircraft systems (UASes) and spaceborne high-resolution imaging systems to assist the Royal Gorge Field Office (RGFO) with mine production

verification. For several RGFO mines, the BLM has developed preliminary fine-scale (approximately one-meter) digital surface model elevation products derived from WorldView-2 and WorldView-3 stereo imagery acquired in late 2015 and 2016 that document elevation changes due to ore extraction and tailings accumulation. These WorldView-derived products provide a current depiction of surface cover; they also fill a gap between, and are complementary to, broader-scale elevation data (e.g., National Elevation Dataset [NED]) and datasets derived from fine-scale systems (e.g., UAS flown at close range).

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 data, multispectral aerial imagery, and sonar data are used to generate maps of topography, vegetation, and river channel bathymetry, which guide restoration activities.

Dam-Failure Flood Inundation Modeling, Mapping, and Life-Loss Consequences Analysis

BOR performs dam-failure inundation modeling and mapping in support of emergency evacuation planning and dam safety risk analysis. Interferometric Synthetic Aperture Radar (IFSAR), lidar, and other geospatial terrain data are used within an Esri ArcGIS environment for pre- and post-processing of numeric hydraulic models. Hydraulic modeling employs one- and two-dimensional modeling techniques and relies primarily on the models produced with MIKE software by DHI (formerly Danish Hydraulic Institute). Inundation modeling results are used to create maps and are overlaid with residential census data to estimate affected populations at risk. This work is an integral component of emergency action plans for dams and provides data for estimating the potential for life loss from dam failure.

Minute 319: Colorado River Delta: Colorado River Delta—Water for the Environment and Environmental Benefits

First-ever plans to facilitate and promote actions that foster environmental benefits in the Colorado River Delta were set in motion by a historic binational agreement known as Minute 319, which was signed in 2012 by the United States and Mexico. The agreement included a science-based plan for a one-time "pulse flow" release of 105,392 acre-feet (130 million cubic meters) of water from the Morelos Dam near Yuma, Arizona, in March 2014. Remotely sensed images are being used to document the effects of this flow. Pre-pulse baseline vegetation information is being derived from WorldView-2 satellite imagery and lidar data; Landsat and MODIS data will be used for analyses of the post-pulse biologic and hydrologic effects. Scientific investigations continued in 2016. More information can be found at *http://www.usbr.gov/lc/region/feature/minute319.html*.

San Joaquin River Restoration Program

The San Joaquin River Restoration Program (SJRRP) is a comprehensive, long-term effort to revive the river's self-sustaining Chinook salmon fishery by restoring water flows to the river from the Friant Dam to the confluence of Merced River, a distance of over 100 miles. A goal of the SJRRP is to mitigate or avoid adverse water supply impacts from the restoration releases. To satisfy this requirement, BOR's Technical Service Center (TSC) has been tasked with completing the design of a compact bypass that provides fish passage around Mendota Pool as well as floodplain grading and revegetation over this reach of the river. In support of these efforts, TSC staff developed lidar-based terrain models to test the hydraulic behavior of the proposed designs. More information can be found at *http://www.restoresjr.net/*.

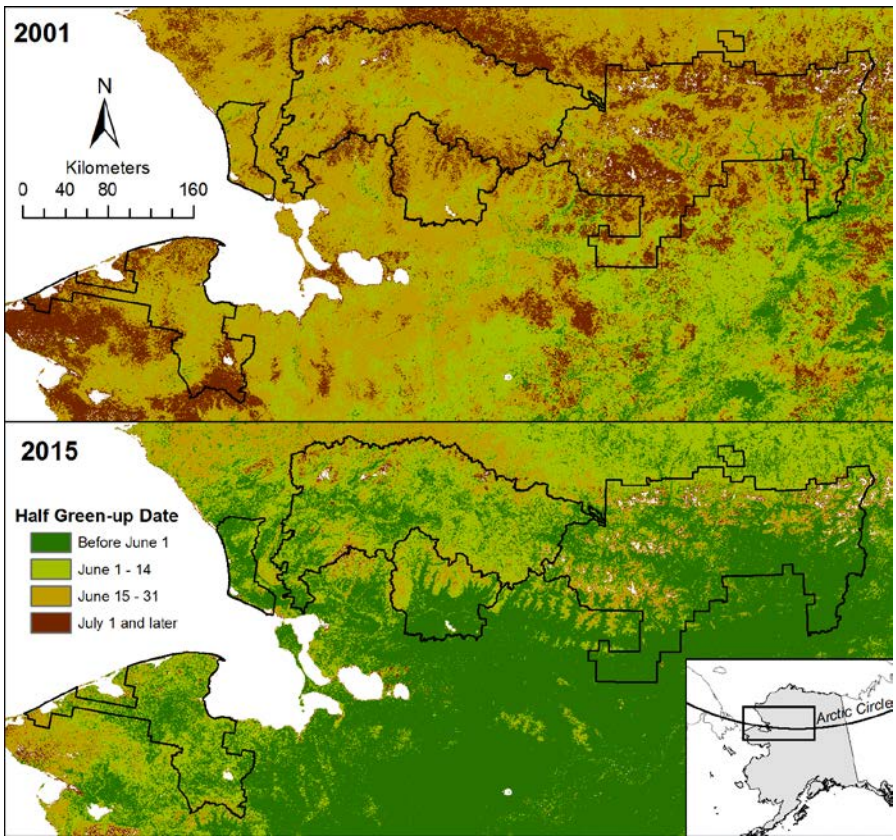
National Park Service

The National Park Service (NPS) has a substantial investment and long history in using aerial and spaceborne remote sensing and GPS technologies. The NPS

Inventory and Monitoring Program conducts baseline inventories for more than 270 parks across the Nation. Remote sensing data are a critical source of information regarding geology, soils, vegetation, and infrastructure. Aerial photography and satellite imagery have been utilized to compile vegetation maps; a monumental task given that the agency is responsible for over 30 million acres. These data are particularly critical for NPS activities in Alaska because of its remote and vast expanses of public land and the fact that the Arctic is warming rapidly in response to climate change. The NPS takes advantage of the free Landsat archive to quantify decadal changes in glacier ice cover and document land-cover change in national park units. NPS has been the DOI sponsoring agency to map all large wildland and prescribed fires as part of the DOI Monitoring Trends in Burn Severity project, using the Landsat archive. GPS supports field data collection, navigation, and search-and-rescue operations conducted by the agency.

Growing-Season Monitoring in Alaska's Arctic National Parks: Arctic Inventory and Monitoring Network

The length and warmth of the growing season is changing in arctic Alaska, with important implications for wildlife and overall ecosystem productivity. The NPS in Alaska is monitoring vegetation using EROS MODIS (eMODIS) weekly composite Normalized Difference Vegetation Index satellite data, a measure of vegetation greenness. The NPS Arctic Inventory and Monitoring Network (the five national parks in northern Alaska), in cooperation with the University of Alaska Fairbanks (UAF) Geographic Information Network for Alaska (GINA), have processed the available eMODIS collection (2000–15) to obtain growing-season metrics for each year, including the date of the start of the green season, the date of the midpoint of spring green-up, maximum greenness, the date of the midpoint of fall senescence, and the date of the end of the green season (*http://www.gina.alaska.edu/projects/modis-derived-ndvi-metrics*). Results show large year-to-year variations in the magnitude of maximum summer greenness and the timing of green-up and senescence. The timing of spring green-up can vary by almost a month between years; green-up is closely linked to the warmth of the spring and early summer and the timing of snow loss. Trend analysis across the 16-year period of record shows that in recent



These maps show the date of the midpoint of spring vegetation green-up in the national parks of northern Alaska (outlined in black). The upper image is from 2001, a year with late green-up, and the lower image is from 2015, a year with early green-up.

years, spring green-up has arrived about a week earlier than it did in the early 2000s, but maximum summer greenness has generally not increased. Information on the timing of spring helps biologists understand the reproductive success of wildlife such as Dall's sheep. More information can be found at *http://science.nature.nps.gov/im/units/arcn/vitalsign.cfm?vsid=28*.

Lake Ice Phenology of Southwest Alaska

Reductions in the duration of annual lake ice cover in Alaska are expected to produce profound environmental changes. These include biological productivity changes in aquatic and terrestrial ecosystems, reduced albedo, and shifts in the timing of ice-jam flooding—all of which impact human activities, including

transportation and subsistence. The duration and seasonality of lake ice are sensitive to wind, air temperature, and snow accumulation and are correlated with climate variability and change. To help understand these dynamics, the Southwest Alaska Network of the NPS Inventory and Monitoring Program is using MODIS satellite data to analyze lake ice phenology—the freeze and break-up timing of lake ice—for 17 southwestern Alaska lakes and lake clusters from 2001 to 2016.

Near-daily 250-meter-resolution visible, near-infrared (NIR), and shortwave infrared (SWIR) reflectance data from the MODIS Terra and Aqua sensors are used in this analysis. The frequent imagery collection allows the detection of ice cover on lakes as it forms, collects snowfall, intermittently thaws, refreezes, and clears when lake extents are free of cloud cover. A grid-based mapping approach to estimate percentages of lake area covered by ice is accomplished through supervised classification using a one-square-kilometer grid in which each grid square is given a value of ice-covered (50–100 percent ice cover) or ice-free (0–49 percent ice cover) status for each day of the year that the areal lake extent is visible. Calibration and validation of results is accomplished using ground-based observations from lake temperature arrays and remote automated weather stations. Correlation is apparent between increased air temperature and reduced lake ice cover and duration.

The analysis produced a dataset of daily percent lake ice cover for each of 17 lakes or lake clusters with dates for initial freeze-up (days with greater than 10 percent but less than 90 percent ice cover), complete ice cover (days with greater than 90 percent ice cover), break-up (days after complete cover with less than 90 percent but more than 10 percent ice cover), and complete exposure (days with less than 10 percent ice cover). Data for 2001–16 will be published and available from the Southwest Alaska Network. The use of these data in collaborative research to investigate the interaction between lake ice phenology on aquatic and terrestrial ecosystems is ongoing and encouraged. More information can be found at *http://science.nature.nps.gov/im/units/swan/monitor/lake_ice_about.cfm*.

Satellite Imagery Used for Sitka Alaska Landslide Response

A heavy rain event on August 18, 2015, triggered two landslides in the southeastern Alaska community of Sitka. The slides claimed three lives and caused substantial damage to property and infrastructure. Approximately 40 other slides occurred in the surrounding area on the same day. One outcome of the local, state, and Federal response to the disaster was the formation of the Sitka GeoTask Force, a multi-agency scientific work group that is studying the meteorological and geotechnical conditions leading up to the event to help the community better prepare for similar events in the future. As part of the task force, the NPS worked with the U.S. Geological Survey's Commercial Remote Sensing Policy (CRSSP) and the Hazards Data Distribution System (HDDS) to provide new and archived satellite imagery to assist with the analysis of past landslide phenomena and the evaluation of future risk. In the months that followed the slides, over 120 Landsat 7/8 and WorldView 2/3 scenes were made available to participating agencies through the HDDS Explorer distribution portal. The imagery serves as a valuable resource for responders, community planners, and scientists by providing an inexpensive and detailed view of a large, remote area in southeastern Alaska. The imagery has been used by the task force to assess soil stability, update existing landslide inventory datasets, aid situational awareness for responders, and create predictive models of landslide hazards. More information can be found at *http://www.sitkascience.org/wp-content/uploads/2011/02/Sitka-Geotask-Force-Summary-Final-2016.pdf*.

Bureau of Indian Affairs

The Bureau of Indian Affairs (BIA) applies remote sensing to activities such as planning land use, responding to non-point-source pollution affecting subsistence hunting and fishing, ameliorating climate-change effects such as sea-level rise for coastal tribes, locating and identifying potential dam hazards, and generating digital terrain data for the use of open-channel hydraulics.

Vegetative Response to Water Availability on the San Carlos Apache Reservation

On the San Carlos Apache Reservation in east-central Arizona, vegetation types such as ponderosa pine forests, pinyon-juniper woodlands, and grasslands have important ecological, cultural, and economic value for the tribe. This value extends beyond the tribal lands and across the western United States. Vegetation across the southwestern United States is susceptible to drought conditions and fluctuating water availability. Remotely sensed vegetation indices can be used to measure and monitor spatial and temporal vegetative response to these water and drought dynamics. USGS scientists derived the Modified Soil Adjusted Vegetation Index II (MSAVI2) from MODIS imagery to measure the condition of three dominant vegetation types (ponderosa pine forest, woodland, and grassland) in response to two fluctuating environmental variables: precipitation and the Standardized Precipitation Evapotranspiration Index (SPEI). The analysis, conducted for 2002 through 2014, showed that grassland and woodland have a similar moderate to strong, year-round, positive relationship with both precipitation and SPEI. This result suggests that these vegetation types respond negatively to drought conditions and are more susceptible to initial precipitation deficits. Ponderosa pine forest had a comparatively weaker relationship with monthly precipitation and summer SPEI, indicating that it is more buffered against short-term drought conditions. This research highlights the response of multiple dominant vegetation types to seasonal and interannual water availability and demonstrates the effectiveness of multitemporal remote sensing imagery as a tool for the detection of vegetation response to climate change at regional scales. Such tools can provide cost-effective monitoring to inform management of drought-affected areas. More information can be found at *https://www2.usgs.gov/climate_landuse/lcs/projects/vcarbon.asp* and *http://geography.wr.usgs.gov/science/TribalLandVegetation/index.html*.

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 2016 related primarily to commercial communications satellites and Earth observation satellites, as well as experimental satellites.

The FCC took several significant actions in administrative and rulemaking proceedings in FY 2016. As part of an overall FCC process reform initiative, on December 17, 2015, the FCC adopted changes to the FCC rules that apply to most satellite communications services. The FCC revised over 200 rules and definitions and eliminated unnecessary rules. Among the major changes are:

- modifying the FCC's process for submitting orbital and spectrum coordination filings to the International Telecommunication Union (ITU) in order to facilitate the international frequency coordination of new U.S. satellite networks;
- simplifying the FCC's rules requiring timely satellite construction and modifying the related financial performance bond requirement in order to discourage the filing of speculative license applications and encourage the surrender of licenses that will not be used; and
- modifying the FCC rules concerning 2° spacing between geostationary satellites in the fixed satellite service to support the increasing use of small earth station antennas.

The FCC also launched a new electronic form for documenting the technical characteristics of the operation of space stations seeking FCC approval and created a single Web page listing all space stations approved under the FCC rules for commercial satellite services.

On July 14, 2016, the FCC adopted rule changes designed to harmonize the operations of commercial satellite services with terrestrial services, including next-generation mobile service, in certain frequency bands. As part of this proceeding, known as "Spectrum Frontiers," the FCC adopted rules on spectrum sharing that will enable the agency to continue to authorize satellite operations in the 27.5- to 28.35-gigahertz (GHz) and 37.5- to 40.0-GHz frequency bands while also opening these frequency bands to additional mobile uses.

On August 15, 2016, the FCC adopted an order revising licensing procedures for nongeostationary space stations.

In FY 2016, the FCC authorized a number of commercial communication satellite deployments and operations. These authorizations included the following:

- **October 29, 2015:** To Skynet Satellite Corporation, to construct, deploy, and operate a Ku- and Ka-band satellite at the longitude 15° west orbit location.
- **February 25, 2016:** To Intelsat License, LLC, to construct, deploy, and operate a C-, Ku-, and Ka-band satellite at the longitude 60° west orbit location.
- **May 11, 2016:** To DirecTV Enterprises, LLC, to construct, deploy, and operate a Ku-band satellite at the longitude 43.1° west orbit location.
- **June 9, 2016:** To Intelsat License, LLC, to construct, deploy, and operate a C- and Ku-band satellite at the longitude 68.5° east orbit location.
- **July 6, 2016:** To Horizons-3 License, LLC, to construct, deploy, and operate a C- and Ku-band satellite at the longitude 169° east orbit location.
- **September 15, 2016:** To Hughes Network Systems, LLC, to construct, deploy, and operate a Ka-band satellite at the longitude 97.1° west orbit location.

During FY 2016, the FCC granted authority to three companies—Spire Global, Inc.; Planet Labs, Inc.; and Terra Bella Technologies, Inc.—to deploy and operate

nongeostationary small satellites in low-Earth orbit, primarily for remote sensing activities. The specifics follow:

- **March 18, 2016:** To Spire Global, Inc., for nine satellites to be deployed at orbital altitudes at or below 435 kilometers.
- **June 6, 2016:** To Terra Bella Technologies, Inc., for one satellite to be deployed in an orbit with a perigee of 502 kilometers and an apogee of 510 kilometers.
- **June 15, 2016:** To Planet Labs, Inc., for up to 600 satellites during a 15-year license term to be deployed at orbital altitudes between 350 kilometers and 660 kilometers.
- **June 16, 2016:** To Spire Global, Inc., for an additional 20 satellites to be deployed at orbital altitudes between 400 and 550 kilometers.
- **August 31, 2016:** To Terra Bella Technologies, Inc., for an additional 12 satellites to be deployed at orbital altitudes between 400 and 630 kilometers.
- **September 15, 2016:** To Planet Labs, Inc., to permit 56 of the 600 previously authorized satellites to operate in an orbit with a perigee of 450 kilometers and an apogee of 720 kilometers.

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 given to universities and institutions conducting research and developing new spacecraft technologies. The satellites' missions included testing new equipment for use on satellites; demonstrating small-spacecraft proximity operations; demonstrating high-speed optical data transmission; and making Earth observations, including imaging. Other experimental licenses granted in FY 2016 included grants to SpaceX to test prototype satellites for the provision of broadband service, as well as grants for space-to-space communications between the Globalstar, Inc., nongeostationary satellite system and certain CubeSats.

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

- **August 1, 2016:** The FCC granted Iridium Constellation, LLC, a license modification to include authority to construct, deploy, and operate 66 nongeostationary satellites, as well as 15 spare satellites, as second-generation satellites to replace its existing satellite system. Iridium's second-generation satellite system will continue to provide mobile voice and data services, with improved voice quality and enhanced data transmission speeds. It will also provide aeronautical mobile-satellite route service to oceanic, polar, and remote areas. This service concerns the safety and regularity of flights.
- **September 1, 2016:** The FCC granted special temporary authority to Intelsat License, LLC, for 180 days to move its Galaxy 11 satellite to the longitude 45° east orbit location and to operate there consistent with Germany's ITU filings.

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

- **June 23, 2016:** The FCC added New Skies Satellite B.V.'s SES-10 satellite to the permitted list, operating under the authority of Colombia and using the Ku-band at the longitude 67° west orbit location. SES-10 was approved, in part, to replace the service provided by the AMC-3 and AMC-4 space stations at the same orbit location.
- **July 12, 2016:** The FCC added SES Satellites (Gibraltar) Ltd.'s SES-15 satellite to the permitted list, operating under the authority of the United Kingdom (Gibraltar) and using the Ku- and Ka-bands at the longitude 129.15° west orbit location. SES-15 was approved, in part, to replace the service provided by the AMC-1 space station at the same orbit location.
- **July 21, 2016:** The FCC added Empresa Argentina de Soluciones Satelitales, S.A.'s ARSAT-2 satellite to the permitted list, operating under the authority of Argentina and using the C- and Ku-bands at the longitude 81° west orbit location.
- **August 31, 2016:** The FCC added Telesat International Limited's Telstar 19 Vantage satellite to the permitted list, using the Ka- and Ku-bands at the longitude 63° west orbit location. The Telstar 19 Vantage satellite will

operate under the authority of Brazil for Ka-band operations in Brazil and for all Ku-band operations, and under the authority of the United Kingdom, on behalf of the Isle of Man, for Ka-band operations outside of Brazil.

In addition, the FCC took action on the following requests for non-U.S.-licensed space stations to provide service in the United States on a nonroutine basis:

- **April 7, 2016:** At the request of Inmarsat plc, the FCC made a modification to the "ISAT List," a list of approved satellites in the Inmarsat mobile-satellite service system that U.S. earth stations may access, to add the Inmarsat-3 F5 satellite at the longitude 54° west orbit location.
- **June 30, 2016:** The FCC granted the applications of Panasonic Avionics Corporation and Gogo, LLC, for earth stations aboard aircraft to communicate with the Yamal 300K satellite operating in the Ku-band under the authority of Russia at the longitude 177° west orbit location. The Yamal 300K satellite was also separately authorized to communicate with the Denali 20020, LLC, earth station in the state of Washington.
- **August 5, 2016:** The FCC granted Hawaii Pacific Teleport, LP's application for its Hawaii earth station to communicate with the JCSAT-2B satellite operating in the Ku-band under the authority of Japan at the longitude 154° east orbit location.

U.S. Department of Agriculture

USDA

Farm Service Agency

Since the 1930s, the Farm Service Agency (FSA) has been tasked with administering farm commodity, credit, conservation, disaster, and loan programs as laid out by Congress through a network of Federal, state, and county offices. Historically, geospatial systems and data have played a fundamental role in FSA's program delivery.

FSA's core spatial dataset, the Common Land Unit (CLU) layer, is a dynamically updated, nationally consistent digital dataset representing farm and field boundaries. Integrated with associated nonspatial farm data in a common foundational system, it allows producers to provide core information and, leveraging advancements in geospatial technology, helped the agency ensure accurate and consistent information of annual commodity plantings. FSA used geospatial data, including the CLU, to support producer crop-reporting activities and the administration of conservation, commodity, and lending programs.

Remotely sensed data, such as Moderate Resolution Imaging Spectroradiometer (MODIS), Advanced Wide Field Sensor (AWiFS), and other high-resolution aerial and satellite imagery collected as a result of interagency coordination, are examples of imagery sources used during periods of 2016 disaster recovery—like the Texas and Louisiana flooding events—to support FSA disaster programs such as the Emergency Loan and Emergency Conservation Programs.

As the primary source of aerial imagery for the U.S. Department of Agriculture (USDA), FSA continues to administer the National Agriculture Imagery Program

(NAIP), leveraging partnership funds from other Federal, state, and local entities to acquire imagery during the growing season over the contiguous United States. In 2016, FSA acquired nearly 1.5 million square miles of four-band (natural-color and near-color-infrared) imagery in 22 states. FSA also made the imagery available through the Early Access Web Services (EAWS) to all states in which imagery was acquired. EAWS provided minimally processed NAIP imagery Web services, direct from flying contractor to end customer, between two and seven days after acquisition. This allowed FSA and partner agencies to perform time-sensitive quality service checking with the most current imagery available months in advance of receiving production-level NAIP imagery.

In addition to distributing the most up-to-date NAIP imagery, FSA also hosted a large imagery archive that was accessible to Federal agencies and the public through the USDA Geospatial Data Gateway. FSA has begun digitizing its extensive historical imagery to eventually be made available for service providers, and these digital records will be archived at the National Archives and Records Administration.

Foreign Agricultural 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 for the USDA's monthly World Agricultural Supply and Demand Estimates (WASDE) report, the primary source of the USDA's global commodity outlook. In FY 2016, the monthly WASDE reports provided public access to information that affected world food security and was crucial to decisions involving U.S. agriculture, trade policy, and food aid. FAS/OGA used satellite imagery at regional, national, and subnational scales to operationally monitor and analyze monthly changes in global crop production. FAS archived and displayed global monthly crop production, supply, and distribution (PSD) data from the USDA's WASDE report on the FAS PSD Online Web site (*https://apps.fas.usda.gov/psdonline/*).

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 Landsat 8 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) imagery, and the GLAM Web interface easily allowed public users to analyze and compare current crop conditions with past years' crop conditions (*https://glam1.gsfc.nasa.gov*). FAS hoped that VIIRS would be operationally ready this year, but the lack of a cross-calibrated time series (with MODIS) pushed the start date to 2017 or later. FAS worked on processes to supplement Landsat imagery with Sentinel-2 imagery.

FAS/OGA also maintained several public global agricultural datasets by processing, archiving, and displaying on the Web a variety of satellite imagery products. 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) satellite network, NOAA's Polar-orbiting Operational Environmental Satellites (POES), ESA's Proba-V, and 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 Topography Experiment (TOPEX)/Poseidon, Jason-1, and Jason-2 satellites. See *http://www.pecad.fas.usda.gov/cropexplorer* for more information.

FAS/OGA is part of the early-adopter program for Soil Moisture Active Passive (SMAP). As an operational user, FAS relies on the Agricultural Research Service (ARS) and NASA researchers to provide the process to ingest SMAP products.

FAS/OGA managed the USDA's Satellite Imagery Archives (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 2016, the USDA/FAS purchased satellite imagery with 22-meter spatial resolution from the Deimos-1 and UK-DMC2 satellites and archived it via SIA's AE. The USDA's National Agricultural Statistics Service

used the Deimos-1 and UK-DMC2 satellite imagery covering the lower 48 U.S. states to map crop type for the 2016 United States crop season and to monitor crop damage caused by natural disasters such as drought, fires, diseases, or insects. FAS/OGA/SIA provided funding to USGS/EROS to process Indian Space Research Organisation (ISRO) Advanced Wide Field Sensor (AWiFS) and Linear Imaging Self Scanner (LISS) imagery. The ISRO imagery will help fill needed temporal and spatial resolution gaps for coverage of the United States.

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; administer and manage 155 national forests and 20 national grasslands collectively known as National Forest System (NFS) lands, totaling 193 million acres; and provide 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 2016, 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:

- Collected comprehensive Earth Observing System (EOS), MODIS, and Suomi NPP VIIRS direct-broadcast data and Landsat 8 OLI data via the USGS's EROS for the United States and Canada. Provided operational processing and dissemination of near-real-time fire-mapping and geospatial data products to fire managers and the general public. (*https://fsapps.nwcg.gov/afm/*)
- Continued activities with NASA Goddard Space Flight Center's Direct Readout Laboratory under a USFS-NASA interagency agreement to test and operationally implement 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. (*https://directreadout.sci.gsfc.nasa.gov/*)

- Coordinated with the GSFC Direct Readout Laboratory to plan and execute the Ninth NASA Direct Readout Conference in June 2016. The meeting focused on the use of real-time Earth observations from NASA's EOS, Suomi NPP instrument data, similar Earth observation assets from international space agencies, and related data-processing/analysis technologies to support the enhancement of decision-support systems.
- Continued operational processing and analysis of MODIS and Landsat imagery for systematic detection of forest damage and changing forest health conditions in our Nation's forests. (*http://foresthealth.fs.usda.gov/portal/Flex/FDM?dL=0*)
- Continued to distribute 250-meter forest attribute data surfaces derived from MODIS imagery and other geospatial predictor data using nearest neighbor imputation methods. (*http://data.fs.usda.gov/geodata/rastergateway/forest_type/index.php*)
- Continued to distribute 250-meter forest carbon estimates derived from MODIS imagery and other geospatial predictor data using nearest neighbor imputation methods. (*http://data.fs.usda.gov/geodata/rastergateway/biomass/index.php*)
- Continued coordination with NASA Ames Research Center to overhaul and update Autonomous Modular Sensor (AMS) electronics and sensor components and further develop the AMS onboard processing system capabilities and user interface to support operational integration flights on USFS aircraft.
- Continued coordination with Goddard Space Flight Center on the testing and evaluation of the Multi-Angle Implementation of Atmospheric Correction (MAIAC) for MODIS, along with its potential use for land and atmospheric remote sensing applications.
- Operationally applied Earth Observing 1 Advanced Land Imager Landsat 7 Enhanced Thematic Mapper (ETM) and Landsat 8 OLI imagery to respond to approximately 231 requests to map the location, extent, and severity of large wildfires to support post-fire emergency stabilization/

hazard mitigation activities and forest restoration planning/management activities. (*http://www.fs.fed.us/eng/rsac/baer* and *https://www.fs.fed.us/postfirevegcondition/index.shtml*)

- Continued to operationally apply Landsat 4/5 Thematic Mapper (TM) and Landsat 7 ETM 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 2016 included the completion of more than 19,000 fires covering more than 140 burned acres between the years 1984 and 2015. (*http://www.mtbs.gov*)
- Continued coordination with the University of Maryland and NASA, under the auspices of a NASA Research Opportunities in Space and Earth Sciences (ROSES) A35 Wildfires Project, to further implement the 375-meter VIIRS I-band active fire detection product as part of operational USFS strategic fire detection and monitoring program activities. Also, coordinated with NASA Goddard Space Flight Center Direct Readout Laboratory to implement the VIIRS algorithm within the global direct-readout processing framework and ensure its availability to direct-readout data practitioners throughout the world. (*https://fsapps.nwcg.gov/afm/*)
- Coordinated with the University of Maryland, NASA, and the USGS, under the auspices of a NASA ROSES A35 Wildfires Project, to execute and test Sentinel 2 prototype active fire detection algorithms (complementing Landsat 8 algorithms implemented in FY 2015) and conduct preliminary evaluation of derived output products to support USFS operational fire support activities.
- Continued technology transfer activities between the USFS and Ames Research Center regarding unmanned aircraft systems and related technologies under the auspices of the NASA-USFS Wildfire Research Applications Partnership and a USFS-NASA interagency agreement. (*http://geo.arc.nasa.gov/sge/WRAP/index.html*)
- Coordinated with Ames Research Center on advancing the Thermal Mapping Airborne Simulator (TMAS) (developed under the NASA

Small Business Innovation Research program) and the Staring Wide Area Imager (StareWAI) to higher Technology Readiness Levels.

- Used imagery from Landsat 5 TM and 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.
- Completed Tree Canopy Cover (TCC) data for the continental United States, Alaska, Hawaii, Puerto Rico, and the U.S. Virgin Islands using imagery from Landsat 5 and Landsat 8 OLI and NAIP as part of the Multi-Resolution Land Characteristics Consortium (MRLC) National Land Cover Database (NLCD) 2011 update and also initiated production on NLCD TCC 2016.
- Expanded the use of Landsat TM/ETM/OLI time-series stacks to detect and monitor forest land-cover change from the mid-1980s to the present in the watersheds of the Great Lakes and all national forests in the Pacific Northwest. This activity is now being conducted using automated change-detection capabilities in the Google Earth Engine.
- Used Landsat TM/ETM/OLI and NAIP imagery in conjunction with other core geospatial datasets to conduct ecological 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. (*http://www.fs.fed.us/eng/rsac/programs/teui/about.html*)
- Progressed toward a comprehensive and consistent land-cover/land-use monitoring system, the Landscape Change Monitoring System (LCMS), for the continental United States. LCMS utilizes Landsat TM/ETM/OLI time-series stacks to detect and monitor land-cover/land-use change from the mid-1980s to the present across all administrative ownerships. This effort is being conducted in collaboration with several Federal and academic partners. (*http://larse.forestry.oregonstate.edu/lcms-landscape-change-monitoring-system* and *http://landsat.gsfc.nasa.gov/?p=10868*)
- Continued to develop standards and practices for integrating lidar into forest and resource management (e.g., defining acquisition specifications, data-quality assessment, and analysis/modeling procedures for forest parameters).

- 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.
- Provided support to NASA Applied Remote Sensing Training (ARSET) program training activities/workshops, including the "Remote Sensing for Wildfire Applications" workshop at Idaho State University in October 2015. Also, continued collaboration to enhance NASA and Forest Service remote sensing training programs and leverage existing Forest Service training investments to increase awareness about emerging technologies and practical resource applications.

National Agricultural Statistics Service

The National Agricultural Statistics Service (NASS) used remote sensing data to construct and sample area frames for agricultural statistical surveys and to estimate crop area and yield. It also continued contributing to two NASA science grants on fallowed California agricultural land and a flood-disaster-based crop loss assessment system. Additionally, NASS published papers describing the development of crop-specific area frame stratifications based on geospatial crop frequency and cultivation data layers and a comprehensive remote sensing assessment of crop yields and MODIS products.

NASS used Landsat imagery, digital NAIP orthophoto quadrangles, and other remotely sensed inputs for the contiguous United States and Puerto Rico to select the yearly area-based samples for the June Agricultural Survey. In addition, NASS updated new area-based sampling frames for Nebraska and Wisconsin.

NASS continued to utilize a new geospatial Cropland Data Layer (CDL)–based automated stratification method for area sampling frame operations, resulting in nine updated state area frames built at reduced cost with improved objectivity and efficiency, along with a 29 percent improvement in accuracy. The CDL data were 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 remote sensing acreage estimation program used Disaster Monitoring Constellation (DMC) and Landsat data to produce crop acreage estimates for crops at the state and county levels during the 2016 crop year. Acreage estimates were created for all market-sensitive crops and states. NASS's Agricultural Statistics Board (ASB) was able to utilize the remote sensing acreage indications as independent input for setting the official estimates for its monthly Crop Production Reports. Analysts derived remote sensing–based acreage indications from the CDL. The primary satellite imagery inputs were from the FAS SIA, which provided growing-season coverage with DMC imagery through a cooperative partnership while utilizing growing-season Landsat 8 imagery. In addition, NASS distributed the CDL for 48 states to stakeholders for the previous 2015 crop season via the USDA Geospatial Data Gateway and the CropScape data visualization portal at *https://nassgeodata.gmu.edu/CropScape*.

NASS utilized NASA MODIS NDVI products for modeling corn and soybean yield indications over the 12 largest production states. Updated yield estimates were delivered operationally to the ASB as an independent indication for setting official August, September, and October yield estimates by state, district, and county. MODIS Land Surface Temperature (LST) products served as an independent variable for yield estimation.

NASS is developing a Decision Support System, in collaboration with researchers from the University of Florida and University of Nebraska, to improve yield forecasts using crop indicators obtained during critical stages of the crop's growing season. A study was conducted that focuses on the evaluation of the potential use of satellite data, crop simulation models, and/or mathematical models to develop critical crop indicators. Research objectives included 1) the determination of corn and soybean phenological critical stages; 2) how critical stages can be predicted or identified using remote sensing, mathematical models (i.e., crop simulation models), and/or a combination of these techniques; 3) how to retrieve and relate information about soil moisture, spectral reflectance, and other available products during critical stages; and 4) how to develop metrics at critical stages or critical crop indicators to improve corn and soybean yield forecasts.

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 work on a NASA science grant titled "Fallowed Area Mapping for Drought Impact Reporting and Decision Making," to which NASS contributed monthly growing-season CDL-based fallowed land estimates for California water resource stakeholders.

NASS investigated using the NASA SMAP mission products for U.S. cropland soil moisture monitoring and assessment. NASS is collaborating with NASA, the Agricultural Research Service, and George Mason University in prototyping a Web-based operational cropland soil moisture monitoring and assessment based on NASS operational Web-based vegetation condition geospatial application within the VegScape system. The prototyped system will provide regular and frequent revisit cycles of both top- and sub-soil moisture observations with complete continental United States coverage.

NASS is collaborating 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 from a NASA research grant titled "A Remote-Sensing-Based Flood Crop Loss Assessment Service System (RF-CLASS) for Supporting USDA Crop Statistics and Insurance Decision Making." 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.

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 2016, AST, in partnership with Europe, Canada, Japan, the Republic of Korea, and Taiwan, continued science operations of the Atacama Large Millimeter/submillimeter Array (ALMA), an interferometer located near San Pedro de Atacama, Chile. ALMA received over 1,500 observing proposals, the most for any observatory on the ground or in space. New capabilities offered to the community included very-long-baseline interferometry with a global network of other telescopes, solar observing, and spectral line polarization observations. A scientific conference highlighted results from the first five years of ALMA and covered 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.

AST continued its oversight of the Daniel K. Inouye Solar Telescope (DKIST—previously referred to as the Advanced Technology Solar Telescope, or ATST), the next-generation U.S. ground-based solar telescope. 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 late 2019/early 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. In August 2013, the National Science Board approved a new baseline cost for the DKIST project of $344.13 million. Construction of the telescope enclosure is nearly complete, and fabrication of the major telescope subsystems and instruments is ongoing. The project is approximately 70 percent complete and is both on budget and on schedule. Construction of the DKIST facility is led by the NSO. In August 2014, the National Science Board approved the renewal of the cooperative agreement for the management and operations of the NSO for a period of ten years.

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 (GEO)/Atmospheric and Geospace Sciences (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. The White House Office of Science and Technology Policy (OSTP) hosted an event rolling out the NSWS entitled "Enhancing National Preparedness for Space-Weather Events." This increased level of awareness of space weather has resulted in focused attention concerning the data products provided by NSO's Global Oscillations Network Group (GONG) facility. 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. Operations of the refurbished GONG facility will be jointly funded through an Interagency Agreement between the NSF and the National Oceanic and Atmospheric Administration signed in August 2016.

Construction of the Large Synoptic Survey Telescope (LSST) project continued in FY 2016, with allowances for realized risks remaining comfortably within the available cost and schedule contingencies calculated at the beginning of the project. Only a few significant contracts remain to be finalized. With construction approaching one quarter completed, some future tasks are being replanned and fleshed out in more detail, benefiting from lessons learned to date. 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. There have been some small delays absorbed by schedule float, and construction is still on schedule for "first light" in 2020. Two years of subsequent commissioning will shake down and tune all the complex interrelated operating systems. The NSF and the Department of Energy (DOE) expect full science observing to start in 2022 and to generate 30–40 terabytes of data every night, night after night, for at least ten years. DOE is funding the camera in a project led by the SLAC (originally Stanford Linear Accelerator Center) National Accelerator Laboratory. The 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. Long-lead-time items and technology development essential for mitigating risks identified early in the project came from private funding. The NSF and DOE will support installation and commissioning together and will augment their operations funding by negotiated contributions from international partners. The LSST project has strong support worldwide.

AST's Mid-Scale Innovations Program (MSIP) granted new multi-million-dollar five-year awards to a number of astronomy projects in FY 2016, including 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; the Hydrogen Epoch of Reionization Array (HERA), for construction of 240 14-meter-diameter low-frequency radio telescopes 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; and Subaru Measurement of Images and Redshifts (SuMIRE), a camera and observing program developed by Princeton for use on the Japanese telescope Subaru on Mauna Kea in Hawaii, to conduct a very deep optical survey of distant galaxies. Awards were also made to provide 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.

Ongoing MSIP programs in FY 2016 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) on Cerro Toco and 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, 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.

Division of Physics

The Division of Physics (PHY) continued to operate its Laser Interferometer Gravitational-Wave Observatory (LIGO), which in FY 2016 announced the groundbreaking direct detection of gravitational radiation from a pair of massive black holes rapidly in-spiraling to merge into a single black hole with a mass equal to 62 times the mass of the sun. The event occurred at a distance of 1.3 billion light years, and its final merger stage as observed by LIGO took less than half a second. This major discovery was decades in the making, following the development, construction, upgrade, and operation of LIGO, which has two observatory sites—one in Hanford, Washington, and the other in Livingston, Louisiana. The characteristic signal of a merging black hole system was seen simultaneously at both sites. A second robust merger detection was also made during FY 2016.

Complementing LIGO, the Division of Physics, in partnership with AST, continued its funding of a new Physics Frontiers Center awarded the previous year 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 a number of 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 single black hole or pair with millions of times the mass of the sun, in contrast to LIGO's tens to hundreds of solar masses, 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

The Geospace Section (GS) within the Division of Atmospheric and Geospace Sciences (AGS) supported a wide variety of research programs in space science in FY 2016. 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 for ground-based solar telescopes and instruments, and a wide-ranging portfolio of basic research in space physics. Major GS-funded activities in FY 2016 included the Geospace Facilities (GF) program; the Space Weather Research (SWR) program; the Coupling, Energetics, and Dynamics of Atmospheric Regions (CEDAR) program; the Geospace Environment Modeling (GEM) program; and the Solar, Heliosphere, and INterplanetary Environment (SHINE) program.

The NSF implemented the GS's Faculty Development in Space Sciences (FDSS) Program in FY 2004 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. A new space physicist was hired as tenure-track faculty at the University of Illinois at Urbana-Champaign under the FDSS program in FY 2016.

Also in FY 2016, the GS continued to support its program for CubeSat-based small-satellite science missions for geospace and atmospheric research and education. During FY 2016, 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 2016. Development efforts also continued on another seven projects for future CubeSat launches that will add new capabilities and breadth to the overall CubeSat program.

In FY 2016, 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. Such storms can cause major disruptions of power and communications systems on the ground. The data collection for AMPERE continued during FY 2016, and the addition of new data and software updates to the AMPERE data server facility made the data freely available to researchers.

Throughout FY 2016, the Community Coordinated Modeling Center (CCMC) for space weather research, cosponsored by the NSF (GS of AGS) and NASA and located at NASA's Goddard Space Flight Center, continued to provide the research community with access to state-of-the-art space weather models and conducted important model-validation activities necessary for transitioning research models into operational use.

Research facilities remained as the key component of GS efforts. In FY 2016, the Geospace Facilities program continued to enable basic research on the structure and dynamics of Earth's upper atmosphere. In particular, the CEDAR and GEM programs conducted research utilizing these facilities. Throughout FY 2016, observations made by the Advanced Modular Incoherent-Scatter Radar (AMISR) at Poker Flat, Alaska, demonstrated the unique capabilities of this new instrument, including its ability to image the ionospheric effects of auroral particle precipitation in three dimensions. These observations provided a wealth of data particularly useful to modelers interested in validating space weather models. A second AMISR system has been operating at Resolute Bay in Arctic Canada since 2009. In FY 2016, new high-quality data were generated from upgrades made to the Resolute Bay Incoherent Scatter Radar (RISR)–C facility at the end of FY 2015. 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.

The GS solar physics community also continued to benefit from AST's ongoing efforts to develop and manage the DKIST being constructed in Hawaii. In FY 2016 and in part through a new award cofounded with AST, the GS continued to provide oversight for much-needed upgrades at the Owens Valley Solar Array in California.

In FY 2016, 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 2016, four of the six COSMIC satellites remained operational (well beyond their expected life cycle), providing 1,000 to 1,500 radio occultation profiles per day. 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, including GPS/Meteorology (GPS/MET), the CHAllenging Mini-satellite Payload (CHAMP), Satélite de Aplicaciones Científicas (SAC-C), Meteorological Operational satellite programme–A/Global navigation satellite system Receiver for

Atmospheric Sounding (METOP-A/GRAS), METOP-B/GRAS, TerraSAR-X, the Gravity Recovery and Climate Experiment (GRACE), and the Communications/Navigation Outage Forecasting System (C/NOFS). The NSF and NASA are jointly funding the COSMIC mission.

NSF continued to collaborate with NOAA, USAF, Taiwan, and UCAR to ensure the success of the follow-on COSMIC-2 mission. The NSF-funded laser retroreflectors were assembled in FY 2016. These will allow more precise orbital determination, which will be beneficial for applications, including better determination of the mean geoid.

Division of Polar Programs

For FY 2016, the primary activities of the Division of Polar Programs (PLR) in ground-based space science and astronomy included continued full-scale observations at the U.S. Amundsen-Scott South Pole Station with the 10-meter off-axis South Pole Telescope (SPT), the battery of five small-aperture (25-centimeter) telescopes called the Small Polarimeter Upgrade for Degree Angular Scale Interferometer (SPUD) array, and another small-aperture telescope called Background Imaging of Cosmic Extragalactic Polarization (BICEP3) that observed in concert with the SPUD array.

The SPT (with the SPT polarization-sensitive [SPTpol] polarization receiver) and the BICEP3/SPUD array are focused currently on measurements of the CMB polarization anisotropy. On large angular scales, they target measurements of the B-mode polarization imprinted by primordial gravitational waves, as well as the B-mode signal caused by the gravitational lensing of the intrinsic CMB's E-mode 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. In December 2016, the SPT will be upgraded with a new, next-generation receiver, SPT-3G, and wide-field optics to continue measuring the CMB polarization with much higher sensitivity.

Recent scientific results from SPT include 1) cosmological constraints from the 2,500-square-degree Sunyaev-Zel'dovich (SZ) effect survey, including improved dark-energy constraints; 2) a search for orphan Gamma Ray Burst afterglows at

millimeter wavelengths (with one candidate found), thus opening a new window on transient astronomy; 3) active and growing SPT and Dark Energy Survey collaborative analysis that includes CMB lensing tomography; 4) detection of kinematic SZ effect (kSZ); and 5) CMB-lensing shear and photo-z calibration.

Recent scientific results from the BICEP Collaboration include deep multi-frequency (95-, 150-, and 220-GHz) maps of degree-scale B-mode polarization that measure gravitational lensing and foregrounds to unprecedented precision and place leading constraints on primordial gravitational waves.

The High Elevation Antarctic Terahertz (HEAT) robotic telescope, deployed since 2011 at the highest point of the Eastern Antarctic Plateau (Ridge A), completed its successful operation through FY 2016 and will be removed and shipped back to the home institution. Scientific data collected throughout the lifetime of this project will be processed and analyzed for publications, and the original observational data will be shared with the scientific community.

The IceCube Neutrino Observatory (jointly operated at the South Pole by the NSF's Division of Polar Programs and Division of Physics) has now collected data for almost six 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. In FY 2016, the ICNO Collaboration reported approximately 100 high-energy neutrino events that exceeded 50 teraelectronvolts (TeV) and came from anywhere in the sky. (One electronvolt [eV] is the energy an electron or proton gains when it is accelerated by a voltage of one volt; one TeV is a trillion eV; two eV is about the energy of a photon in the visible orange light band.)

IceCube identified the first astrophysical high-energy neutrino flux ever, with the significance at 5.7 sigma level after analyzing three years of collected data (2010–13), and by now a few extremely high-energy events (over one petaelectronvolt [PeV] = 1,000 TeV) were recorded by ICNO in the range from 1.0 to 9.0 PeV. The search for very-high-energy neutrinos is primarily driven by the quest for discovering the origin and nature of cosmic rays; however, the dozens of astrophysical neutrinos observed so far do not yet allow the identification of any individual source. Nevertheless, the surprisingly high level of the neutrino flux observed implies that a significant fraction of the energy in the non-thermal universe is

generated in hadronic accelerators. These are the first "pixels" of the first picture of the distant neutrino universe—an excellent confirmation of IceCube's having opened the doors to a new era in particle astrophysics.

The Division of Polar Programs also supports NASA's Long Duration Balloon (LDB) Program in the Antarctic, providing at McMurdo Station the necessary logistics for astrophysics payload assembly and final testing, then helping to launch the balloons and organize and support payload recovery after LDB termination 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 understanding of and support for U.S. national space policies and programs. State supports U.S. civil space activities through the negotiation of bilateral and multilateral agreements with partner countries and leads U.S. participation in numerous international space and technological activities and international organizations.

In FY 2016, the DOS Office of Space and Advanced Technology (SAT) within the Bureau of Oceans and International Environmental and Scientific Affairs (OES) continued to lead the U.S. delegation to the United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS) and supported its Legal (LSC) and Scientific and Technical (STSC) subcommittees. DOS also continued to lead the participation of both U.S. Government and private-industry participation in the Working Group on Long-Term Sustainability (LTS) of Outer Space Activities; during the June 2016 Committee meeting, the U.S. delegation facilitated consensus on 12 of the LTS-proposed 26 voluntary "best practice" guidelines submitted by various member countries. The delegation was influential in consolidating many of the proposed guidelines concerning policies; regulatory frameworks and practices that support the sustainability of the outer space activities; international intergovernmental organizations authorizing or conducting space activities; safety of space operations; and international cooperation and awareness. In FY 2017, U.S. participation in the LTS Working Group and intersessional meetings will continue, with a goal of achieving consensus on the remaining, more contentious guidelines. To ensure alignment with U.S. space and foreign policy goals, DOS contributed to the development of the seven thematic priorities and the agenda

for the 50th anniversary of the first United Nations conference on the Exploration and Peaceful Uses of Outer Space (UNISPACE+50) planned for 2018; State will serve in a leadership role for a new action team to develop a plan of activities to be approved in 2018, as well as identifying a mechanism for coordinating global space exploration efforts.

DOS continued to promote space weather as an important foreign-policy topic worldwide, and during the February 2016 COPUOS STSC conference, the United States and Canada organized a Space Weather Workshop under the auspices of the Space Weather Expert Group. Topics of discussion included the assessment of recommendations and priorities established by international bodies; an overview of national and international efforts; actions to advance the priorities of the U.N. Committee on Space Research (COSPAR)/International Living With a Star (ILWS) Space Weather Roadmap, including possible routes to implementation; and the refining of the Expert Group Work Plan. Building off this momentum, the Committee agreed to include an "international framework for space weather services" as one of seven thematic priorities to commemorate UNISPACE+50 at its 59th session (2017).

DOS participated in the interagency Space Weather Operations, Research, and Mitigation Task Force, which drafted the 2015 National Space Weather Strategy and the National Space Weather Action Plan. With NOAA, DOS co-led the interagency team focused on Goal 6: "Increase International Cooperation"; State also hosted international workshops and meetings, sustained U.S. participation in relevant United Nations activities, and raised awareness for space weather among our international partners to support the goal. In April 2016, State-OES/SAT and the Secure World Foundation convened a panel discussion called "Space Weather as a Global Challenge" (*https://2009-2017.state.gov/e/oes/sat/spaceweather/index.htm*). This public event brought together top space weather experts from government, industry, and academia to discuss the international aspects of the recently released space weather strategy and to inform policy makers of the potential impacts of space weather on infrastructure and the global economy.

In November 2015, the United States hosted the 10th anniversary meeting of the International Committee on Global Navigation Satellite Systems (ICG) in Boulder, Colorado, under DOS leadership. This meeting brought together more

than 200 experts and government officials representing more than 20 countries and organizations to discuss global navigation satellite systems (GNSS) service provision and their use in a multilateral forum. The four ICG working groups include 1) Systems Signals and Services; 2) Enhancement of GNSS Services Performance; 3) Information Dissemination and Capacity Building; and 4) Reference Frames, Timing, and Applications. Results of the working groups were 12 recommendations adopted by the full ICG in an effort to improve GNSS compatibility and interoperability, as well as to improve outreach to the user community.

DOS also continued to promote the use of GPS in Africa, working through the AfricaArray consortium and the United Nations Office of Outer Space Affairs (UNOOSA). AfricaArray is a public-private partnership led by academic researchers at both the University of the Witwatersrand in South Africa and Pennsylvania State University. The organization focuses on supporting training and research in Earth, atmospheric, and space sciences in Africa. At the AfricaArray annual meeting, held January 11, 2016, in Johannesburg, South Africa, OES/SAT facilitated the travel of scientists from over 12 Sub-Saharan African countries to participate in workshops and training sessions on a broad spectrum of Earth and space sciences.

The U.S. hosted the eighth U.S.-European Union bilateral Space Dialogue in December 2015. The discussions focused on a number of different topics, including space sciences and research, Earth observation, and GNSS. In Earth observation, the United States and the European Union signed a "Copernicus Cooperation Arrangement" on October 16, 2016. As a result, European Sentinel satellite data are now being shared across the Atlantic Ocean for disaster management, climate change monitoring, and a multitude of Earth science applications through the Copernicus Coordination Group (CCG), which brings together remote sensing experts from both sides to enable more effective exchange of information.

Working-level discussions with the European Union on GNSS also continued in FY 2016 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, including aviation applications, met in October 2015 and April 2016 and has continued to make progress on Advanced Receiver Autonomous Integrity Monitoring (ARAIM), publishing a Milestone 3 report in FY 2016. The working group on trade and civil

applications met in December 2015 and March 2016. In August 2016, U.S. and EU delegations met to discuss and reiterate U.S. interest in negotiating access to the EU Public Regulated Service (PRS) signal. The European Union gained approval for its security-related Common Minimum Standards for PRS in June 2016, which was followed by a negotiating mandate given to the European Commission.

DOS continued to lead productive bilateral meetings in FY 2016 with China. In October 2015, the Subgroup on Aviation Augmentations and Applications met in Washington, DC, to discuss the Chinese Satellite Based Augmentation System (SBAS) and other aviation-related topics. In May 2016, the United States and China met on the margins of the China Satellite Navigation Conference in Changsha. This conference included another meeting of the Aviation Subgroup, as well as the Subgroup on Compatibility and Interoperability, where the discussions focused on GNSS signals and improved interoperability. Another bilateral meeting of the Subgroup on Compatibility and Interoperability took place in September 2016 in Portland, Oregon, on the margins of the U.S. Institute of Navigation's GNSS+ 2016 Conference.

On June 27, 2016, DOS facilitated an Expert Workshop on Satellite Collision Avoidance and Orbital Debris Mitigation with China as a followup to the first U.S.-China Civil Space Dialogue held in September 2015 in Beijing. Topics of discussion included further collaboration related to space debris and the long-term sustainability of outer space activities, as well as an exchange of views on coordination and communication related to satellite collision avoidance.

DOS conducted the second U.S.-Vietnam civil space talks to promote Vietnam's increasingly active role in regional and global space activities. The dialogue took place in Hanoi, Vietnam, in December 2015, and focused on new projects covering space weather, space geodesy, space technologies to manage the Mekong Delta, and the exchange of Earth observation data. The discussion also covered the use of global navigation satellite systems, orbital debris mitigation, and maritime domain awareness. DOS encouraged Vietnam to accede to the UN Outer Space treaties and to develop national space legislation. The United States and Vietnam continued to work toward finalizing a civil space framework agreement.

The second U.S.–Republic of Korea (ROK) Civil Space dialogue was held on April 27, 2016, in Seoul, South Korea. The U.S. Ambassador, Mark Lippert,

and ROK Minister of Foreign Affairs Yun Byung-Se signed the Cooperation in Aeronautics and the Exploration and Use of Airspace and Outer Space for Civil and Peaceful Purposes Framework Agreement. The signing ceremony symbolizes the commitment President Barack Obama and President Park Geun-hye made during their summit meeting in October 2015 to expand space cooperation in certain areas. The dialogue focused on the importance of space exploration and continued economic and technological progress between our two alliances. The United States highlighted two main points: the increase in activity by the private sector in the U.S. civil space sector and the importance of space weather operations research and mitigation. The United States also encouraged the ROK to play a stronger role in multilateral activities. Both sides overwhelmingly agreed that the dialogue was a success, and they agreed to hold the next dialogue in Washington, DC, in 2017.

At the request of the Republic of Korea, DOS held a bilateral dialogue in Washington, DC, in September 2016 regarding U.S. export control reforms as they relate to the export of U.S.-manufactured components for the ROK's next series of Earth observation satellites. The ROK sought to better understand the recent changes in the DOS International Trade and Arms Regulations (ITAR) regime and the space-related components that have been moved to the Department of Commerce's Commerce Control List (CCL). The dialogue offered the ROK an insight into the U.S. interagency process and mechanisms for better communication on export control activities between the two nations.

As part of Secretary John Kerry's "Safe Ocean Network" initiative, DOS conducted the second Civil Maritime Domain Awareness (CMDA) workshop in Hanoi, Vietnam, with support from the U.S. Naval Research Laboratory and Pacific Command (PACOM) in September 2016. The workshop concentrated on strengthening and enhancing Vietnam's maritime situational awareness, focusing on the technological foundations for space-based vessel detection, processing, visualization, and analysis—the capacities that contribute to combating illegal, unreported, and unregulated fishing; illegal wildlife and human trafficking; disaster management; customs and border protection services; and port planning and navigational safety systems.

A space dialogue with Ukraine took place on May 24, 2016, cochaired by State/OES/SAT and the State Space Agency of Ukraine. U.S. Federal departments and

agencies presented an overview of U.S. space policy, including implementation of the June 2010 National Space Policy directive, and such space activities as space exploration, satellite data and remote sensing, and global navigation satellite systems. The two sides discussed areas for potential future cooperation and current developments in both countries' space programs. The participating organizations agreed that discussions on cooperation would continue through a range of bilateral agency-to-agency–level mechanisms as well as through relevant international multilateral venues.

Department of Energy

DOE

The Department of Energy (DOE) participates in the national effort to further U.S. interests in space. Three organizations within DOE provide this capability: the National Nuclear Security Administration's (NNSA) Office of Defense Nuclear Nonproliferation Research and Development (DNN R&D), the Office of Science (SC), and the Office of Nuclear Energy (NE).

Office of Defense Nuclear Nonproliferation Research and Development

The Nuclear Detonation Detection program 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 (NuDets). The Space-Based Nuclear Detonation Detection (SNDD) subprogram provides much of the Nation's capability to detect, report, locate, and identify nuclear explosions using orbiting satellites. SNDD 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. NuDet 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, the SNDD subprogram 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, DNN R&D 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 Los Alamos National Laboratory (LANL), Sandia National Laboratories (SNL), and Lawrence Livermore National Laboratory (LLNL)—supply the science, technology, and engineering required for USNDS. LANL and SNL lead the production of sensor-laden payloads, and LLNL contributes to the end-to-end modeling of USNDS. These laboratories have a unique and comprehensive understanding of nuclear weapons, as well as the observables associated with nuclear detonations and the propagation of signals to sensors. Moreover, these laboratories have extensive capabilities in the design, construction, calibration, deployment, and operation of satellite-based instruments, along with detailed modeling and analysis. To support continuous global monitoring, the operations communities routinely receive analysis, insights, and computer codes based on this research.

Two payload suites built at the NNSA laboratories accomplish the NuDets 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, DNN R&D 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.

Office of Science

In FY 2016, the Office of Science 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 fundamental research in plasma science that contributes to SC-NASA mutual interests in knowledge of heliospheric and astrophysical systems. Some of the research supported by SC's Office of Fusion Energy Sciences (FES) advances the development of a comprehensive understanding of heliospheric and astrophysical magnetized-plasma processes, including Alfven wave acceleration of auroral electrons, magnetic reconnection and turbulent processes in Earth's magnetosphere and the solar corona, the formation and evolution of astrophysical jets, and dynamo processes creating planetary/galactic magnetic field structures. Specific examples included 1) the Large Plasma Device (LAPD) at the Basic Plasma Science Facility (BaPSF) at the University of California, Los Angeles, which enables controlled studies of Alfven waves that carry energy and momentum from the sun to Earth and throughout the universe; 2) the Magnetic Reconnection Experiment (MRX) at the Princeton Plasma Physics Laboratory (PPPL), which permits laboratory studies of magnetic reconnection and particle energization processes in Earth's magnetotail and solar flares; and 3) 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 research, such as increased understanding of the role of dusty plasmas in planetary rings and interstellar media, the properties of plasmas created by hypervelocity impacts, and the properties of warm dense matter similar to that found in planetary cores. In 2015, FES sponsored a series of community-led research opportunities workshops to identify compelling scientific challenges at the frontiers of plasma physics, with workshop reports delivered in 2016. Attention was paid to opportunities in the next decade. Plasma science governing space weather was highlighted, an area of broad mutual interest to NASA and FES. Furthering the study of laboratory plasmas for growing our understanding of astrophysical plasma phenomena was also a focus.

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. 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 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 would include experimental operations and data analysis. In 2016, AMS published results of its measurement of the cosmic-ray antiproton spectrum using the first four years of data. The precision of the spectral measurement is unprecedented and provides experimental information, over the largest extended energy range to date, in the study of elementary particles travelling through space. Novel features are seen that as yet are unexplained. Previously, the collaboration published key results that placed constraints on models of energetic cosmic-ray electrons, positrons, protons, and helium, including on the existence of dark matter.

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 does a complete survey of the entire sky in high-energy gamma rays every three hours and enables searches for transient phenomena over a wide range of timescales. SC managed the LAT fabrication and now operates the LAT Instrument Science Operations Center. In 2016, FGST published results in its search for a signal from gravitational wave sources in conjunction with the Laser Interferometer Gravitational-Wave Observatory, which announced in February 2016 the first-ever direct detection of gravitational waves emanating from the coalescence of two black holes. Although no signal in gamma rays was observed, the results provided limits on the presence of transient counterparts to the gravitational wave signal. SC also made crucial contributions to the European Space Agency–NASA Planck cosmic microwave background satellite mission. Planck measures the cosmic microwave background, which allows studies of the inflationary epoch in the early universe, as well as dark energy, dark matter, and

neutrino properties. A Memorandum of Agreement (MOA) signed between NASA and DOE provided dedicated National Energy Research Supercomputing Center (NERSC) computing resources for the Planck mission.

SC and NASA also engaged in many collaborative research efforts in the areas of atmospheric science and terrestrial ecology. In FY 2016, SC's Atmospheric Radiation Measurement Climate Research Facility (ARM) activity provided a cloud spectrometer and impactor (CSI) aircraft instrument to support NASA's Olympic Mountain Experiment (OLYMPEX) measurement campaign in the Pacific Northwest region of the United States. The overall purpose of the campaign was to improve remote sensing retrievals of cloud and precipitation properties in winter storms from over the ocean to over complex terrain in support of the NASA Global Precipitation Measurement mission.

During FY 2016, SC's ARM and Terrestrial Ecosystem Science (TES) activities supported aircraft measurements of atmospheric trace gases in Oklahoma to improve understanding of the influence of atmospheric and terrestrial processes on atmospheric carbon dioxide concentrations. DOE coordinated flights under the NASA Tropospheric Emission Sounder and Orbiting Carbon Observatory 2 (OCO-2) satellites for the testing of carbon dioxide retrievals. 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 OCO-2 satellite. SC's ARM activity also included support for 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 validation of algorithms for the Cross-track Infrared Sounder and Advanced Technology Microwave Sounder on the Suomi National Polar-orbiting Partnership satellite and future Joint Polar Satellite System satellites.

The TES activity is participating in the interagency Carbon Cycle Science topic of the 2016 NASA Research Opportunities in Space and Earth Sciences solicitation on Arctic/boreal ecosystems research. SC's Next Generation Ecosystem Experiment (NGEE)–Arctic is working 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 (CO_2),

and methane (CH_4) flux over Barrow and Council, Alaska. An MOA to leverage the complementary expertise between these two activities has been developed; it provides 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 will be used to characterize tropical forest dynamics across a range of edaphic, climatic, and land-use gradients in the Amazon and Puerto Rico to support SC's NGEE-Tropics activity. Through interagency agreements, SC's Atmospheric System Research (ASR) 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 and RHIC was the construction of the Electron Beam Ion Source (EBIS), which extended the range of ion species available for both radiological effects research and fundamental nuclear science; EBIS was fully commissioned in 2015. In 2016, BNL started the "Extended EBIS" upgrade, which will yield benefits to NSRL as a new gas injection system for elements hydrogen (H) to helium (He-4), allowing for effective high-intensity light ion operations.

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 and NASA, along with other stakeholders, have recently initiated a National Academy Study focused on a comprehensive assessment of the future needs of the electronics space-radiation effects testing program in the United States. 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.

In addition, since FY 2001, DOE and NASA have engaged in coordinated efforts to better understand and predict the health risks associated with exposure to low-dose radiation. SC's Low Dose Radiation Research Program has coordinated with NASA's Space Radiation Project within NASA's Human Research Program. The SC Low Dose program focuses on doses of radiation measured at or below current workplace exposure limits; current collaborations are limited due to a decreasing emphasis on human radiation research within SC's research portfolio.

Office of Nuclear Energy

The Office of Nuclear Energy 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.

NE continues to support the next RPS-powered mission, Mars 2020. In FY 2016, NE completed work on the nuclear risk assessment for the NASA National Environmental Policy Act process. In addition, NE initiated the fuel processing of existing Pu-238 stock in FY 2015, as well as continuing to prepare the Safety Analysis Reports to support the nuclear launch approval processes. With NASA funding support, NE continues to work on making enhancements to the current RPS production infrastructure by upgrading equipment for more robust operations, primarily at Los Alamos National Laboratory. In FY 2016, NE and NASA continued to investigate advances in both thermoelectric and Stirling power conversion technologies that could result in more efficient and capable RPSs for NASA's

long-term exploration goals. Advanced thermoelectric technology—developed by NASA's Jet Propulsion Laboratory and showing promising benefits—has been transferred to private industry for final development and manufacturing feasibility. DOE and NASA partnered to review the technology for potential insertion into the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) system as a future system advancement. The technology and its transfer to industry continue to make progress, and a formal technical evaluation process is being initiated for its review. The outcome of the process could lead to a technology insertion into the MMRTG, increasing its performance.

NE continues working with NASA to re-establish domestic Pu-238 production at existing facilities, Oak Ridge National Laboratory and Idaho National Laboratory, in order to ensure continued availability of RPS power systems for future science missions. The project began in FY 2011, is fully funded by NASA, and is managed by NE. In 2016, the project conducted an end-to-end demonstration of chemical processing steps needed to recover Pu-238 from irradiated targets. Fifty grams of Pu-238 oxide was separated and sent to LANL. NE and DOE national laboratories provide key support in the areas of programmatic planning, reactor and system modeling, and fuel development and qualification for NASA's Nuclear Cryogenic Propulsion Stage project, commonly known as Nuclear Thermal Propulsion (NTP). In 2015, the project successfully fabricated and tested a hexagonal four-coolant channel surrogate graphite composite fuel element to temperatures and for durations relevant to proposed Mars missions.

Smithsonian Institution

The Smithsonian Institution continued to contribute to national aerospace goals through a variety of activities in FY 2016. The Smithsonian Astrophysical Observatory (SAO) and the Harvard College Observatory form the Harvard-Smithsonian Center for Astrophysics (CfA) in Cambridge, Massachusetts. Through this organization, more than 300 scientists engaged 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 national aerospace goals through research and education activities.

The most popular news story coming from SAO in FY 2016 was the discovery of a cosmic "death star" that is eating a planet. Researchers found a white dwarf star orbited by several rocky objects and a cloud of dust. These bits of debris are all that remain from a small planet that was ripped apart by tidal forces.

In FY 2016, preliminary findings were announced from the Event Horizon Telescope, a project that unites telescopes around the world to study the event horizon of the massive black hole at the center of the Milky Way. Using the Event Horizon Telescope, scientists for the first time detected magnetic fields just outside the black hole, firmly grounding decades of theoretical work. These magnetic fields drive turbulence within the disk of material near a black hole, allowing the black hole to pull matter inward and convert its gravitational energy into light. The magnetic fields can also launch jets of material moving away from the black hole at nearly the speed of light. Over the next few years, the Event Horizon Telescope will expand its capabilities to produce the first images of black holes and their surrounding magnetic fields.

FY 2016 marked an important milestone for SAO and its international partners on the Giant Magellan Telescope (GMT). On November 11, 2015, these partners celebrated groundbreaking for the GMT in Chile. The ceremony featured President Bachelet of Chile and U.S. Ambassador Michael Hammer. The GMT 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.

The Chandra X-ray Observatory continues to play an important role in the exploration of the universe. SAO controls science and flight operations for the Chandra X-ray Center from its location in Cambridge, Massachusetts.

With its unrivaled ability to obtain high-resolution x-ray data, Chandra has enabled astronomers to investigate phenomena as diverse as comets, black holes, supernova remnants, galaxy clusters, dark matter, and dark energy. Chandra continues to operate at high efficiency, carrying out observations for teams from all over the world. It has high productivity, with an average of 450 publications per year. The community of Chandra users (~4,000) increases by ~190 per year and represents a significant percentage of the international astronomical community.

Chandra science continues to have high visibility and popularity in the press and in social media. For example, in FY 2016, researchers used Chandra and other telescopes to set a new record for the most distant galaxy cluster seen. This galaxy cluster may have been caught right after birth—a brief but important stage of evolution never seen before. Another team used Chandra to discover an extraordinary ribbon of hot gas trailing behind a galaxy like a tail. This ribbon, or x-ray tail, is likely due to gas stripped from the galaxy as it moves through a vast cloud of hot intergalactic gas and is likely the largest such tail ever detected.

During this past year, scientists also used Chandra to make the first detection of x-rays from Pluto as it observed the dwarf planet while the New Horizons mission approached and then passed it in 2015. These observations offer new insight into the space environment surrounding the largest and best-known object in the solar system's outermost regions.

The Solar Dynamics Observatory provides better-than-HD-quality images of the sun's surface and outer atmosphere. 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, allowing us to better understand the physical processes in solar flares.

In 2016, SAO scientists were also involved in the development and assembly of new instruments, including the Solar Wind Electrons Alphas and Protons (SWEAP) Faraday Cup experiment on the Solar Probe Plus mission (which will fly to within 10 solar radii of the sun), the Hi-C II and Marshall Grazing Incidence X-ray Spectrograph (MaGIXS) rockets (which will observe the solar corona while pushing the limits of spatial resolution and x-ray spectral coverage, respectively), and the Air Force Airborne Infrared Spectrograph (AIR-SPEC) experiment (an airplane-borne infrared telescope to observe the 2017 solar eclipse).

NASA's Spitzer Space Telescope, now in its 14th year of operation, has continued to produce exciting new views of the universe at infrared wavelengths. Spitzer is the fourth and final space telescope in NASA's Great Observatory series. Spitzer's Infrared Array Camera (IRAC) was developed at SAO, with Giovanni Fazio as Principal Investigator, and constructed at NASA's Goddard Space Flight Center. SAO scientists, in collaboration with the Spitzer Science Center, continue to play an important role in the operation of IRAC, the data analysis, and the use of Spitzer for astronomical observations.

Spitzer's IRAC, jointly with the Hubble Space Telescope, has been used by SAO scientists to uncover new insights into galaxy birth and evolution in the very early universe. These observations have resulted in the discovery of a remarkably luminous and developed galaxy that existed only ~400 million years after the Big Bang. This is the earliest time such a galaxy has ever been detected. These observations also determined the galaxy's stellar mass, age, and star formation rate.

SAO scientists, using the Spitzer Space Telescope, recently completed a Near Earth Object (NEO) Survey consisting of a total of ~1,000 objects with estimated sizes and reflectivities (albedos). A new series of NEO observations has been initiated that will take place over the next two years and provide another 1,100

measurements, yielding a large and uniform catalog of NEO properties. An independent size distribution of NEOs at 100 meters will be determined that is free from albedo assumptions, addressing a current controversy. Through albedo measurements, the compositional distribution of NEOs will be measured as a function of size. The changes in brightness for nearly 1,000 NEOs will be measured, thus constraining asteroid shapes in addition to sizes and compositions. This catalog will enable a number of other science cases to be pursued by SAO scientists and other researchers. This work was carried out jointly with a group at Northern Arizona University.

In public outreach, SAO continued its popular monthly Observatory Night lectures and observing sessions. Begun by observatory director Harlow Shapley in 1930, these public nights offer the local community an opportunity to learn about the latest advances in astronomy and to view the moon, stars, and planets through a variety of telescopes. Observatory Night talks also reach worldwide audiences via YouTube.

In FY 2016, SAO partnered with Project Decathlon to conduct international outreach to Ghana in West Africa. Ten SAO astronomers gave oral interviews for the astronomy portion of this project, which reaches more than 1,000 students. SAO also served as a liaison between Project Decathlon and Astronomers Without Borders to provide 300 pairs of eclipse glasses so that Ghanaian students could witness a September 1 annular eclipse of the sun safely.

"The Dynamic Sun," an exhibit conceived, designed, and built by SAO researchers, expanded to new locations via temporary exhibits in the Harvard Art Museum's Lightbox Gallery and at North Carolina State University. This exhibit features a giant video wall intended to create a visceral impact and show visitors how an ever-changing sun affects Earth. The original "Dynamic Sun" at NASM in Washington, DC, continues to be seen by eight million visitors per year.

In FY 2016, NASM continued to educate and inspire the public through exhibits, research, and education programs, including Discovery Stations; lecture series; family educational events; publications; science, technology, engineering, and mathematics (STEM) Webcasts; and intern training. The annual Exploring Space Lecture Series focused on "Life in the Solar System and Beyond," with presentations on Europa exploration, astrobiology, and exoplanet searches. The annual

John H. Glenn Lecture in Space History featured a conversation on the topic "Spaceflight: Then, Now, and Next" between Apollo 11 astronaut Michael Collins and space entrepreneur Jeff Bezos. Financier and philanthropist David Rubenstein moderated the panel.

For the 40th anniversary of the museum's flagship building on the National Mall, NASM renovated the central Boeing Milestones of Flight Hall, rearranging the iconic aircraft and spacecraft for greater coherence and updating the displays with new exhibit techniques. For this project, both the Mercury Friendship 7 and Gemini IV capsules underwent thorough inspections and cleaning, and the Apollo Lunar (landing) Module-2 (LM-2) was relocated into this hall. LM-2 was inspected, conserved, and reconfigured slightly to represent the Apollo 11 LM-5, Eagle. The Explorer 1 satellite and Pioneer 11/12 spacecraft, which are all suspended from the ceiling, also received treatment and repositioning. A new addition was the fan from the famed National Advisory Committee for Aeronautics' (NACA) wind tunnel used at Langley Research Center in Hampton, Virginia, now mounted prominently on a wall in the Milestones Hall.

Staff members in NASM's Center for Earth and Planetary Studies (CEPS) continued to participate in 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. In FY 2016, Dr. Bruce Campbell served as a cochair for the Next Mars Orbiter study group. CEPS staff members also serve on the science teams for the Mars Science Laboratory (Curiosity), 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), the radar sounder on ESA's Jupiter Icy Moons Explorer (JUICE), the Lunar Reconnaissance Orbiter (LRO), the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft, and the Radar for Icy Moon Exploration (RIME) radar sounder on the Europa Clipper Mission. CEPS continued its active research program in planetary and terrestrial geology and

geophysics with research on such topics as comparative planetology; Martian fluvial, aeolian, and volcanic features; and radar studies of the moon, Venus, and Mars.

NASM's Archives added several significant collections to its holdings this year. The Robert Truax Papers contain the papers of his career as naval officer detailed to the Air Force for top-secret projects, and later as a corporate aerospace executive and an entrepreneur. The ILC Dover Apollo Reports and Aperture Card Drawings Collection contains the drawings and reports of the ILC engineering development and manufacturing company. The company is best known for being awarded the prime contract for the Apollo spacesuits. ILC designed and manufactured the suit worn by Apollo astronauts, including the 12 who walked on the moon. The Fred Weick Papers contain the papers covering Weick's work as an aeronautical engineer. While working for the NACA, he developed the NACA low-drag cowling for radial engines (1928) and built a low-landing-speed aircraft as an independent project sparked by a series of light-aircraft design seminars at the NACA's Langley Research Center (1931).

The NASM Archives processed the Sally Ride Papers and the Arthur C. Clarke Collection. Both collections are available online on the Smithsonian Online Virtual Archive at *http://sova.si.edu/*.

In July 2016, the NASM Archives received over one million digital files from the Gale Cengage Digitization Project. The digital assets and the accompanying metadata will be reviewed by the staff for quality and accuracy, and a workflow will be developed for ingesting the assets in the Digital Asset Management System (DAMS) of the Smithsonian. The digital files will then be available to Smithsonian staff and researchers worldwide.

The NASM Space History and Aeronautics departments maintained a brisk pace of aerospace historical research and publication, with 170 journal articles, books and book chapters, magazine articles, reviews, and blog posts published in FY 2016. Articles appeared in the *Encyclopedia of Planetary Landforms*, *Geology*, *Geophysical Research Letters*, *History and Technology*, *Icarus*, the *Journal of Geophysical Research*, *Physics Today*, *Quest: The History of Spaceflight Quarterly*, *Science*, *Technology and Culture*, and others. Dr. John D. Anderson published the sixth edition of his renowned *Fundamentals of Aerodynamics*, a text used in aerospace education

worldwide. Research and publication reflect the Smithsonian's dedication to the "increase and diffusion of knowledge" and are a primary channel for expanding public awareness of the technical and cultural dimensions of aerospace history.

NASM added several significant aerospace artifacts to the National Collection via excess property transfers from NASA. These included flight hardware from the Hubble Space Telescope servicing missions, backup cameras for the Lunar Reconnaissance Orbiter mission, the Robonaut 1 developmental unit, the Space Shuttle–borne Large Format Camera and Spacelab 2 Infrared Telescope, a full-scale model of the Curiosity Mars rover, and a variety of smaller payloads and equipment. Preservation and display of these material artifacts enables the museum to tell the Nation's and NASA's stories of space exploration.

NASM continued its popular series of special-focus family days, often with NASA participation. Space Day, Mars Day, Women in Aviation and Space Day, African American Pioneers in Aviation and Space Day, Hispanic Heritage in Air and Space, and others draw large crowds, primarily families, to participate in hands-on activities and opportunities to meet pilots, astronauts, scientists, and engineers. NASM has expanded its *STEM in 30* [minutes] Webcasts and *What's New in Aerospace* broadcasts in cooperation with NASA Television, sending lively programs on hot topics, often with astronaut speakers, to subscribers and classrooms worldwide. These programs effectively broaden public outreach for both the museum and the space agency.

The Smithsonian National Museum of Natural History continued, through the Department of Mineral Sciences and the Offices of Education and Exhibits, its mission of education, research, and curation related to space exploration. In addition to the approximately 1 million people per year who visit the Moon, Meteorites and Solar System Gallery of the Geology, Gems and Meteorites Hall, NMNH conducted two episodes of the award-winning *Science How?* broadcast from the Q?rius learning center, focused on meteorites, with scientists Dr. Tim McCoy and Dr. Catherine Corrigan. NMNH scientists remain actively engaged in spacecraft missions, with Dr. McCoy serving as a co-investigator on the newly launched OSIRIS-REx spacecraft, which will visit asteroid Bennu and return samples to Earth for study. 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. McCoy also participated in the MESSENGER mission to Mercury and is a co-investigator on the Psyche mission, which is being considered by NASA to visit a metallic asteroid; sampling the core of an ancient asteroid will provide the best glimpse of cores like that of our own planet.

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. Finally, NMNH completed a renewal of a three-agency agreement with NASA and the National Science Foundation for the continued collection, description, curation, and distribution of meteorites from Antarctica. This program has collected more than 23,000 meteorites, including samples from Mars, the moon, and numerous poorly known asteroids. These samples have addressed fundamental questions about the origin and evolution of our solar system.

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*	21	3	2	0
* (through September 30, 2016)				
TOTAL	**1769**	**162**	**113**	**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 U.S.

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
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*	23	23			2	24			10	7	1		1	
*(through September 30, 2016)														
TOTAL	**1,524**	**3,045**	**10**	**8**	**93**	**234**	**1**	**1**	**249**	**52**	**8**	**4**	**2**	**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 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, 2015–September 30, 2016

Launch Date Spacecraft Name COSPAR* Designation Launch Vehicle	Mission Objectives	Apogee and Perigee (km), Period (min), Inclination to Equator (°)	Remarks
October 2, 2015 Morelos 3 2015-056A Atlas 5-421	Communications	35,855.5 35,782 1,436.09 6.6	MEXSAT-3 for the Mexican Government
October 8, 2015 NROL 55 2015-058A Atlas 5-401	Military/Communications	1,208.3 1,021.3 107.4 63.4	U.S. National Reconnaissance Office
October 31, 2015 Navstar 75 GPS IIF-11 2015-062A Atlas 5-401	Navigation	20,246.1 20,132.7 718.0 55.0	U.S. Air Force, combined military/civilian Global Positioning System
November 4, 2015 HaikaSat/CubeSats 2015-F03A Super Strypi	International Space Station	FTO	Failed to orbit; first-stage motor malfunction
December 6, 2015 Cygnus/CRS-4 2015-072A Atlas 5-401	International Space Station	ISS	Cargo resupply
December 22, 2015 Orbcomm OG2 2015-081A Falcon 9 v1.2	Communications	720.5 715.5 99.0 47.0	Communications satellite constellation
January 17, 2016 Jason 3 2016-002A Falcon 9 v1.1	Earth observation	1,354.4 1,342.8 112.5 66.0	National Oceanic and Atmospheric Administration's Earth science observation mission
February 5, 2016 GPS IIF-12 2016-007A Atlas 5-401	Navigation	20,259.4 20,219.0 720.0 54.9	Global Positioning System Block 12 (GPS IIF-12) on behalf of U.S. Air Force
February 10, 2016 NROL-45 2016-010A Delta 4M+5,2	Military/communications	1,092.2 1,085.4 106.9 123.0	U.S. National Reconnaissance Office
March 4, 2016 SES 9 2016-013A Falcon 9 v1.2	Communications	35,796.5 35,791.1 1,436.1 0.0	Operated by SES S.A.
March 23, 2016 Cygnus OA-6 2016-19A Atlas 5-401	International Space Station	230.0 229.8 92.0 51.6	Cargo resupply
April 8, 2016 Dragon/CRS-8 2016-024A Falcon 9 v1.2	International Space Station	253 309 51.7	Cargo resupply, delivered Bigelow Expandable Activity Module (BEAM) to ISS
May 6, 2016 JCSAT 14 2016-028A Falcon 9 v1.2	Communications	35,804.1 35,784.5 1436.1 0.0	Japanese Communications SATellite (JCSAT) provides communications services to Asia, Oceania, and Hawaii

* U.N. Committee on Space Research

Appendix B (cont.)

Successful Launches to Orbit on U.S. Vehicles

October 1, 2015–September 30, 2016

Launch Date Spacecraft Name COSPAR* Designation Launch Vehicle	Mission Objectives	Apogee and Perigee (km), Period (min), Inclination to Equator (°)	Remarks
May 27, 2016 Thaicom 8 2016-031A Falcon 9 v1.2	Communications	35,810.8 35,777.4 1,436.1 0.1	Provides communications coverage to India, Thailand, and Africa Built by Orbital ATK, managed by Thaicom PLC of Thailand
June 11, 2016 NROL 37 2016-036A Delta 4 Heavy	Military/Communications	36,009.2 35,579.3 1,436.1 7.4	U.S. National Reconnaissance Office
June 15, 2016 Eutelsat 117 West B 2016-038A Falcon 9 v1.2	Communications	37,166.9 34,459.4 1,437.1 0.1	Also launched ABS-2A
June 24, 2016 MUOS 5 2016-041A Atlas 5-551	Military/Communications	35,170.5 15,249.6 942.9 9.8	Mobile User Objective System (MUOS) for the U.S. Navy
July 18, 2016 Dragon CRS-9 2016-046A Falcon 9 v1.2	International Space Station	250.99 249.18 51.6 92.62	Cargo resupply
August 14, 2016 JCSAT 16 2016-050A Falcon 9 v1.2	Communications	35,876.3 35,863.9 1,440.0 0.0	Japanese Communications SATellite (JCSAT)
August 19, 2016 GSSAP 3/4 (AFSPC 6) 2016-052A Delta 4M+4,2	Military/communications	35,745.9 35,730.9 1,433.3 0.2	Geosynchronous Space Situational Awareness Program (GSSAP) constellation for U.S. Air Force
September 1, 2016 AMOS-6 2016-E01 Falcon 9 v1.2	Communications	FTO	Carried Israeli-built Affordable Modular Optimized Satellite-6 (Amos-6). Launch vehicle and payload destroyed on pad
September 8, 2016 OSIRIS-REx 2016-055A Atlas 5-411	Asteroid sample return mission	Heliocentric Orbit	Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer (OSIRIS-REx) reaches asteroid Bennu in 2018, returns sample to Earth in 2023

Appendix C
HUMAN SPACEFLIGHTS

October 1, 2015–September 30, 2016

Spacecraft	Launch Date	Crew	Flight Time (d:h:min)	Highlights
Soyuz TMA-19M (Expedition 46)	December 15, 2015	Tim Kopra Yuri Malenchenko Tim Peake	185:22:12	Musculoskeletal research to inform future expeditions to Mars
Soyuz TMA-20M (Expedition 47)	March 18, 2016	Jeff Williams Alexey Ovchinin Oleg Skripochka	172:03:22	Installed Bigelow Expandable Activity Module (BEAM) prototype inflatable habitat Jeff Williams set NASA record for cumulative time in space—534 days Orbital ATK's Cygnus CRS OA-6 docked to ISS March 26, 2016 SpaceX CRS-8 docked to ISS April 10, 2016, to deliver BEAM
Soyuz MS-01 (Expedition 48)	July 6, 2016	Anatoly Ivanishin Kate Rubins Takuya Onishi	115:02:21	Installed International Docking Adapters for future commercial vehicles

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	9,655	3,158	178	2,346	87	18	508	22	31,458

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 2016 dollars)

FY	Inflation Factors	NASA Total	NASA Space	DOD[a]	Other[b]	DOE[c]	DOC	DOI	USDA	NSF[d]	DOT	Total Space
1959	6.499	2,151	1,696	3,185	221	221						5,102
1960	6.401	3,354	2,957	3,591	275	275						6,823
1961	6.312	6,085	5,845	5,138	429	429						11,413
1962	6.227	11,364	11,189	8,082	1,239	922	318					20,511
1963	6.164	22,640	22,350	9,554	1,584	1,319	265					33,488
1964	6.089	31,052	30,541	9,736	1,297	1,279	18					41,573
1965	6.015	31,580	30,907	9,468	1,450	1,378	72					41,825
1966	5.912	30,593	29,943	9,985	1,265	1,106	160					41,193
1967	5.787	28,740	27,952	9,630	1,233	1,065	168					38,815
1968	5.616	25,759	24,878	10,793	978	814	157	1	6			36,649
1969	5.430	21,670	20,753	10,930	925	641	109	1	5	169		32,608
1970	5.191	19,447	18,414	8,711	732	535	42	5	5	145		27,857
1971	4.926	16,310	15,276	7,448	798	468	133	10	5	182		23,522
1972	4.689	15,505	14,399	6,597	625	258	145	28	9	185		21,621
1973	4.477	15,247	13,846	7,265	660	242	179	45	9	185		21,771
1974	4.290	13,028	11,835	7,575	678	180	257	39	13	189		20,089
1975	4.007	12,937	11,679	7,580	632	120	256	32	8	215		19,892
1976	3.631	12,889	11,709	7,200	611	84	261	36	15	215		19,520
TQ*	3.395	3,164	2,882	1,562	146	17	75	10	3	41		4,590
1977	3.296	12,585	11,339	7,951	638	73	300	33	20	213		19,928
1978	3.167	12,859	11,475	8,672	716	108	326	32	25	225		20,862
1979	2.968	13,640	11,960	9,010	736	175	291	30	24	217		21,707
1980	2.747	14,393	12,855	10,570	635	110	255	33	38	198		24,060
1981	2.527	13,944	12,615	12,200	592	104	220	30	40	198		25,407
1982	2.302	13,911	12,723	15,372	720	140	334	28	35	183		28,815
1983	2.154	14,806	13,628	19,424	704	84	383	11	43	183		33,756
1984	2.063	15,386	14,149	21,033	814	70	487	6	39	212		35,996
1985	1.993	15,091	13,800	25,443	1,163	68	843	4	30	219		40,406
1986	1.929	15,058	13,819	27,245	919	68	596	4	44	208		41,984
1987	1.886	20,598	18,497	30,713	878	91	524	15	36	211	2	50,088
1988	1.845	16,716	15,351	32,610	1,367	445	649	26	33	212	2	49,328
1989	1.787	19,598	18,040	31,993	1,001	173	538	30	38	216	5	51,034
1990	1.718	21,176	19,691	26,832	869	136	418	53	43	213	7	47,393
1991	1.658	23,244	21,635	23,517	1,281	416	416	48	43	350	7	46,433
1992	1.602	22,930	21,139	24,060	1,278	357	524	54	46	289	6	46,477
1993	1.563	22,371	20,423	22,052	1,143	258	507	52	39	281	6	43,617
1994	1.527	22,249	19,885	20,105	966	113	476	47	47	274	8	40,955
1995	1.494	20,704	18,745	15,907	1,134	89	526	46	48	415	9	35,785
1996	1.463	20,318	18,393	16,849	1,211	67	691	53	54	338	9	36,454
1997	1.437	19,694	17,896	16,847	1,134	50	644	60	56	315	9	35,877
1998	1.412	19,267	17,393	17,447	1,185	145	614	61	55	301	8	36,026
1999	1.394	19,039	17,374	18,411	1,369	146	802	82	52	279	8	37,155
2000	1.377	18,729	17,242	17,820	1,454	226	792	83	61	285	8	36,515
2001	1.349	19,196	17,947	19,325	1,433	196	778	81	49	313	16	38,704
2002	1.317	19,588	18,274	20,736	1,555	219	848	84	37	350	16	40,565
2003	1.296	19,919	18,617	25,136	1,692	248	841	96	54	437	16	45,444
2004	1.272	19,564	18,220	24,317	1,862	266	948	90	78	466	15	44,399
2005	1.241	20,108	18,911	24,443	1,925	284	1,002	87	91	447	15	45,280
2006	1.204	20,007	18,975	26,616	1,982	295	1,035	99	101	438	14	47,573
2007	1.166	18,983	18,147	26,132	1,958	233	1,063	101	76	471	14	46,238
2008	1.135	19,425	18,727	28,139	1,927	221	978	102	67	544	15	48,793
2009	1.112	19,762	19,206	29,493	2,077	222	1,199	71	30	539	16	50,776
2010	1.099	20,579	20,033	29,083	2,260	223	1,386	74	29	532	16	51,376
2011	1.089	20,080	19,498	29,669	2,381	249	1,573	72	21	449	16	51,548
2012	1.068	18,977	18,368	28,483	2,754	212	2,003	81	7	433	17	49,606
2013	1.049	18,240	17,684	10,818	2,703	194	1,956	88	21	429	16	31,731
2014	1.031	17,647	17,081	10,400	2,839	174	2,087	82	19	461	16	31,256
2015	1.014	18,010	17,359	10,325	3,010	182	2,223	83	19	485	18	30,694
2016	1.000	19,285	18,645	9,655	3,158	178	2,346	87	18	508	22	31,458

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. The 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)

Federal Agencies	Budget Authority 2014 actual	2015 actual	2016 actual	2017 est.	Budget Outlays 2014 actual	2015 actual	2016 actual	2017 est.
NASA[1]	17,080.5	17,359	18,645	18,234.7	16,558.7	17,697.4	18,225	18,377
DOD[2, 3]	10,400	10,325	9,655	10,136	11,507	10,854	10,300	10,400
DOE[4, 5]	174	182	178	158	174	198	180	158
DOC[6]	2,087.1	2,223.1	2,346	2,305	1,167.3	1,300.3	2,053	1,361
DOI[7]	82	83	87.1	102	81	82	85.5	109.1
USDA[8]	19.3	18.9	18.5	17.7	18.7	17.3	17.1	17.8
DOT	16	17.6	21.8	24.7	16	17.6	21.8	24.7
NSF[9]	461	485.2	507.5	479.1	391	444.6	382.6	473.06

1. The FY 2017 estimate is based on the prior year's Outlays versus Budget Authority. FY 2017 Enacted Funding Levels were not available at the time this report was requested. The FY 2017 Budget Authority Estimate is based on the 2017 President's Budget Request.
2. Does not include DOD or Office of the Director of National Intelligence (ODNI) intelligence programs. DOD FY 2014, FY 2015, and FY 2016 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. DOD estimates of projected budget outlays are rounded to the nearest hundred million due to the estimating methodology.
4. In prior years, the High Energy Physics program also reported Ground- and Underground-Based Astrophysics Projects. These projects and the associated funding are no longer included, starting in the FY 2009 report.
5. At the time of preparing this report, DOE submitted estimates, not actuals.
6. The Budget Outlays columns reflect dollars "costed" in a fiscal year specific to that same fiscal year's appropriated dollars.
7. The numbers for FY 2014 Actual and Outlays are estimates for both satellite and aerial funding.
8. At the time of preparing this report, the USDA submitted FY 2016 estimates, not actuals.
9. "Actual" = actual obligations.

Appendix D-3

Federal Aeronautics Activities Budget

(in millions of dollars by fiscal year)

	Budget Authority				Budget Outlays			
Federal Agencies	**2014 actual**	**2015 actual**	**2016 actual**	**2017 est.**	**2014 actual**	**2015 actual**	**2016 actual**	**2017 est.**
NASA[1]	566	651	640	790.4	538.7	578.3	609	608
USDA[2]	34.4	26.7	37.3	37.6	32.6	32.6	36.6	37.2
DOD[3, 4]	75,500	50,800	50,557	45,328	68,025	37,744	37,500	31,800
DOI[5]	31	31	36	35	30	31	35	35.6
DOT	2,744	2,741.8	3,004.9	2,990.4	2,851	2,761.1	2,733.9	3,115.9

1. The FY 2017 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. DOD FY 2014, FY 2015, and FY 2016 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.
4. DOD estimates of projected budget outlays are rounded to the nearest hundred million due to the estimating methodology.
5. The numbers for FY 2014 Actual and Outlays are estimates for both satellite and aerial funding.

Acronyms

3DEP	3D Elevation Program

A

AA&S	Aircraft Airworthiness and Sustainment
AAG	Air-to-Air-to-Ground
AATE	Advanced Affordable Turbine Engine
AAVP	Advanced Air Vehicles Program
ABEDRR	Advanced Booster Engineering Demonstration and/or Risk Reduction
ABoVE	Arctic-Boreal Vulnerability Experiment
ACAT/FRRP	Automatic Collision Avoidance Technology/Fighter Risk Reduction Program
ACE	Advanced Composition Explorer
ACES	Atomic Clock Ensemble in Space
ACS	Altitude Combustion Stand
ACT	Atacama Cosmology Telescope
ACT-America	Atmospheric Carbon and Transport–America
ADS-B	Automatic Dependent Surveillance–Broadcast
AE	Archive Explorer
AEFS	Advanced Electronic Flight Strips
AEHF	Advanced Extremely High Frequency
AES	Advanced Exploration Systems
AETD	Adaptive Engine Technology Development
AFB	Air Force Base
AFRICOM	United States Africa Command
AFRL	Air Force Research Laboratory
AFRL/RQ	AFRL/Aerospace Systems Directorate
AFSPC	Air Force Space Command
AFTC	Air Force Test Center
AFTMS	airframe TMS
AGS	Atmospheric and Geospace Sciences
AIA	Atmospheric Imaging Assembly
AIR-SPEC	Airborne Infrared Spectrograph
A-ISR	Aerial Intelligence Surveillance and Reconnaissance
AIT	Accident Investigation Team; American Institute in Taiwan
ALIAS	Aircrew Labor In-Cockpit Automation System
ALMA	Atacama Large Millimeter/submillimeter Array
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
AMSR2	Advanced Microwave Scanning Radiometer 2
AO	Arecibo Observatory
APKWS	Advanced Precision Kill Weapon System
ARAIM	Advanced Receiver Autonomous Integrity Monitoring
ARD	analysis-ready data
ARI	Aviation Restructure Initiative
ARL	Airborne Reconnaissance Low
ARM	Asteroid Redirect Mission; Atmospheric Radiation Measurement Climate Research Facility
ARMD	Aeronautics Research Mission Directorate

ARRM	Asteroid Redirect Robotic Mission
ARS	Agricultural Research Service
ARSET	NASA Applied Remote Sensing Training
ARSTRAT	Army Forces Strategic Command
ARTS	Automated Radar Terminal System
AS	Atmosphere Section
ASB	Agricultural Statistics Board
ASBU	Aviation System Block Upgrade
ASI	Italian Space Agency
ASR	Atmospheric System Research
ASRS	Aviation Safety Reporting System
AST	Office of Commercial Space Transportation; Division of Astronomical Sciences
ASTER	Advanced Spaceborne Thermal Emissions and Reflection Radiometer
ASU	Group on the Sector Understanding on Export Credits for Civil Aircraft (also called Aircraft Sector Understanding)
ATD-1	Air Traffic Management Technology Demonstration–1
ATD-2	Airspace Technology Demonstration 2
ATLO	assembly, test, launch, and operations
ATom	Atmospheric Tomography
ATSR	Along-Track Scanning Radiometer
ATST	Advanced Technology Solar Telescope
Auto ACAS	Automatic Air Collision Avoidance System
Auto GCAS	Automatic Ground Collision Avoidance System
Auto ICAS	Automatic Integrated Collision Avoidance System
AUVSI	Association for Unmanned Vehicle Systems International
AVD	Air Vehicle Demonstrator
AVHRR	Advanced Very High Resolution Radiometer
AWiFS	Advanced Wide Field Sensor

B

BAER	Burn Area Emergency Response
BARREL	Balloon Array for Radiation-belt Relativistic Electron Losses
BaPSF	Basic Plasma Science Facility
BBS	Breeding Bird Survey
BEAM	Bigelow Expandable Activity Module
BIA	Bureau of Indian Affairs
BICEP3	Background Imaging of Cosmic Extragalactic Polarization
BIS	Bureau of Industry and Security
BLAST-TNG	Balloon-borne Large-Aperture Submillimeter Telescope–The Next Generation
BLM	Bureau of Land Management
BNL	Brookhaven National Laboratory
BOR	Bureau of Reclamation

C

CAL	Cold Atom Laboratory
Caltech	California Institute of Technology
CASIS	Center for the Advancement of Science in Space
CBW	Chesapeake Bay Watershed
CCAFS	Cape Canaveral Air Force Station
C-CAP	Coastal Change Analysis Program
CCG	Copernicus Coordination Group

CCL	Commerce Control List
CCMC	Community Coordinated Modeling Center
CCMD	Combatant Commands
CCP	Commercial Crew Program
CCS	Counter Communications System
CCSC	Collaborations for Commercial Space Capabilities
CCSDS	Consultative Committee for Space Data Systems
CCtCap	Commercial Crew Transportation Capability
CDD	Capabilities Development Document
CDL	Cropland Data Layer
CDR	Critical Design Review
CEDAR	Coupling, Energetics, and Dynamics of Atmospheric Regions
CENTCOM	United States Central Command
CEPS	Center for Earth and Planetary Studies
CfA	Center for Astrophysics
CFD	Computational Fluid Dynamics
CHAMP	CHAllenging Mini-satellite Payload
CHARA	Center for High Angular Resolution Astronomy
CLaRe	Climate-Landscape Response
CLASS	Cosmic Large Angular Scale Survey
CLU	Common Land Unit
CMA	Crew Module Adapter
CMB	cosmic microwave background
CMC	ceramic-matrix composite
CMDA	Civil Maritime Domain Awareness
CMM	Coordinate Measuring Machine
CNES	Centre National d'Études Spatiales
C/NOFS	Communications/Navigation Outage Forecasting System
CNT ESR	Carbon Nano-tube Electrical Substitution Radiometer
CO_2	carbon dioxide
CODE	Collaborative Operations in Denied Environment
COE CST	Center of Excellence for Commercial Space Transportation
comsat	communications satellite
CORAL	COral Reef Airborne Laboratory
COSMIC	Constellation Observing System for Meteorology, Ionosphere, and Climate
COSPAR	U.N. Committee on Space Research
COSPAS-SARSAT	Search and Rescue Satellite-Aided Tracking
COWVR	Compact Ocean Wind Vector Radiometer
CPS	Conventional Prompt Strike
CPT	Command Post Terminal
CRP	Commercialization Readiness Program
CRS	Commercial Resupply Services
CRSSP	Commercial Remote Sensing Policy
CS	Commercial Service
CSA	Canadian Space Agency
CSI	cloud spectrometer and impactor
CSIM	Compact Solar Irradiance Monitor
CTOL	Conventional Take-Off and Landing
CuSP	CubeSat to study Solar Particles
CV	Carrier Variant
CWDP	Commercial Weather Data Pilot
CYGNSS	Cyclone Global Navigation Satellite System

D

DAMS	Digital Asset Management System
Data Comm	Data Communications
DB	Direct Broadcast
DC	direct current
DE	directed energy
DEM	digital elevation model
DEVA	Death Valley National Park
DHI	Danish Hydraulic Institute
DIAL	Differential Absorption Lidar
DKIST	Daniel K. Inouye Solar Telescope
DLR	German Aerospace Center
DMC	Disaster Monitoring Constellation
DNH	Do-No-Harm
DNN R&D	Office of Defense Nuclear Nonproliferation Research and Development
DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
DOI	Department of the Interior
DOS	Department of State
DR	Direct Readout
DSAC	Deep Space Atomic Clock
DSCOVR	Deep Space Climate Observatory
DSN	Deep Space Network
DSP	Defense Support Program
DSWE	Dynamic Surface Water Extent
DT-2	Developmental Test 2
DTM	digital terrain model
DTN	Disruption Tolerant Networking
DVE	degraded visual environments

E

EAWS	Early Access Web Services
EBIS	Electron Beam Ion Source
ECMWF	European Centre for Medium-Range Weather Forecasts
ECS	Environmental Control System
ECU	Early Combatant Command Use
EDGE	Europa Deep Geophysical Explorer
EDL	entry, descent, and landing
EELV	Evolved Expendable Launch Vehicle
EFTMS	engine fuel TMS
ELaNa	Educational Launch of Nanosatellites
ELV	Expendable Launch Vehicle
ELVO	Enhanced Low Visibility Operations
EMARSS	Enhanced Medium Altitude Reconnaissance Surveillance System
EMC	Evolvable Mars Campaign
eMODIS	EROS MODIS
EOS	Earth Observing System
EPA	Environmental Protection Agency
EPIC	Earth Polychromatic Imaging Camera
EPS	Enhanced Polar System
ERA	Environmentally Responsible Aviation
ERAM	En Route Automation Modernization

ERAU	Embry-Riddle Aeronautical University
EROS	Earth Resources Observation and Science
ESA	European Space Agency
ESD	Exploration Systems Development; Earth Science Division
E-STA	European Service Module Structural Test Article
ET	evapotranspiration
ETM	Enhanced Thematic Mapper
ETM+	Enhanced Thematic Mapper Plus
EU	European Union
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
EUV	Extreme Ultraviolet
eV	electronvolt
EVA	extravehicular activity
EVE	Extreme Ultraviolet Variability Experiment
EVI	Enhanced Vegetation Index
Ex-Im	Export-Import
EXIS	X-ray Irradiance Sensor
EXPRESS	EXpedite the PRocessing of Experiments for Space Station

F

FAA	Federal Aviation Administration
FAB-T	Family of Advanced Beyond Line-of-Sight Terminals
FAS	Foreign Agricultural Service
FAST	Formulation Assessment and Support Team
FCC	Federal Communications Commission
FDSS	Faculty Development in Space Sciences
FES	Office of Fusion Energy Sciences
FF	Fire and Forget
FGST	Fermi Gamma-ray Space Telescope
FIA	Forest Inventory and Analysis
FIAT	Fire and Invasive Assessment Tool
FOC	Full Operational Capability
FONSI	Finding of No Significant Impact
FORVIS	Forest Vegetation Information System
FSA	Farm Service Agency
FT4	Flight Test Series 4
FUN3D	Fully Unstructured Navier-Stokes 3-Dimensional
FWS	Fish and Wildlife Service
FY	fiscal year

G

GaN	gallium nitride
GBD	Global Burst Detector
Gbps	gigabits per second
GBSAA	Ground Based Sense and Avoid
GBSD	Ground Based Strategic Deterrent
GCD	Game Changing Development
GCOM-W	Global Change Observation Mission–Water
GEM	Geospace Environment Modeling
GEO	Geosynchronous Earth Orbit; Directorate for Geosciences
GF	Geospace Facilities
G-FOLD	Guidance for Fuel Optimal Large Diverts
GHz	gigahertz

GINA	Geographic Information Network for Alaska
GIS	Geographic Information System
GISS	Goddard Institute for Space Studies
GISTEMP	GISS Surface Temperature Analysis
GLAM	Global Agricultural Monitoring
G-LiHT	Goddard's Lidar, Hyperspectral and Thermal
GMT	Giant Magellan Telescope
GNSS	global navigation satellite systems
GOES	Geostationary Operational Environmental Satellite
GOES-R	Geostationary Operational Environmental Satellite-R Series
GOLD	Global-scale Observations of Limb and Disk
GONG	Global Oscillations Network Group
GPIM	Green Propellant Infusion Mission
GPM	Global Precipitation Measurement
GPS	Global Positioning System
GPS/MET	GPS/Meteorology
GPSRO	GPS radio occultation
GRACE	Gravity Recovery and Climate Experiment
GRC	Glenn Research Center
G-REALM	Global Reservoir and Lake Monitor
GS	Geospace Section
GSD	ground sample distance
GSDO	Ground Systems Development and Operations
GSFC	Goddard Space Flight Center
GSSAP	Geosynchronous Space Situational Awareness Program

H

HAPET	Habitat and Population Evaluation Team
HAWKC+	High-Resolution Airborne Wideband Camera-plus
HBCUs	Historically Black Colleges and Universities
HDDS	Hazards Data Distribution System
HEAT	High Elevation Antarctic Terahertz
HEO	Highly Elliptical Orbit
HEOMD	Human Exploration and Operations Mission Directorate
HERA	Hydrogen Epoch of Reionization Array
HIBRID	Higher Bypass Ratio Inlet Development
HIID	HIBRID Inlet Integration Demonstration
HiRISE	High Resolution Imaging Science Experiment
HLV	Heavy Lift Vehicle
HPSC	High Performance Spaceflight Computing
HRP	Human Research Program
HWB	Hybrid Wing Body

I

IBEX	Interstellar Boundary Explorer
ICAO	International Civil Aviation Organization
ICBM	Intercontinental Ballistic Missile
ICG	International Committee on Global Navigation Satellite Systems
ICON	Ionospheric Connection Explorer
ICPS	Interim Cryogenic Propulsion Stage
IDA	International Docking Adapter
IDAC	Integrated Departure/Arrival Capability
IFSAR	Interferometric Synthetic Aperture Radar
IGD	integrated ground demonstration

ILWS	International Living With a Star
IMAP	Interstellar Mapping Probe
IMERG	Integrated Multi-satellitE Retrievals for GPM
INSCOM	Intelligence and Security Command
InSight	Interior Exploration using Seismic Investigations, Geodesy and Heat Transport
INVENT	INtegrated Vehicle Energy Technology
IOC	Initial Operational Capability
IPAD	International Production Assessment Division
IR	infrared
IRAC	Infrared Array Camera
IRIS	Interface Region Imaging Spectrograph
ISARA	Integrated Solar Array and Reflectarray Antenna
Isp	specific impulse
ISR	Intelligence Surveillance and Reconnaissance
ISRO	Indian Space Research Organisation
ISS	International Space Station
ITA	International Trade Administration
ITAC 1	Industry Trade Advisory Committee for Aerospace Equipment
ITAR	International Trade and Arms Regulations
ITEP	Improved Turbine Engine Program
ITU	International Telecommunication Union
ITWS	Integrated Terminal Weather System
IVF	Integrated Vehicle Fluids

J

JAGM	Joint Air-to-Ground Missile
JASD	Joint Agency Satellite Division
JAXA	Japan Aerospace Exploration Agency
JICSpOC	Joint Interagency Combined Space Operations Center
JMR TD	Joint Multi-Role Technology Demonstrator
JMS	JSpOC Mission System
JOTR	Joshua Tree National Park
JPL	Jet Propulsion Laboratory
JSpOC	Joint Space Operations Center
JPSS	Joint Polar Satellite System
JSF	Joint Strike Fighter
JSOW	Joint Standoff Weapon
JUICE	Jupiter Icy Moons Explorer
JWST	James Webb Space Telescope

K

KDP	Key Decision Point
KSC	Kennedy Space Center
kSZ	kinematic SZ
KUS	Kennedy Uplink Station

L

L1	Level 1; Lagrange point 1
L2	Level 2
LAE	Launch Abort Engines
LANL	Los Alamos National Laboratory
LAPD	Large Plasma Device

LaRC	Langley Research Center
LASP	Laboratory for Atmospheric and Space Physics
LAT	Large Area Telescope
LCH_4	liquid methane
LCMAP	Land Change Monitoring, Assessment, and Projection
LCMS	Landscape Change Monitoring System
LCRD	Laser Communication Relay Demonstration
LCS	Launch Communications Station
LDB	Long Duration Balloon
lidar	light detection and ranging
LIGO	Laser Interferometer Gravitational-Wave Observatory
LILT	low-intensity, low-temperature
LISA	Laser Interferometer Space Antenna
LISS	Linear Imaging Self Scanner
LLNL	Lawrence Livermore National Laboratory
LM	Lunar Module
LOX	liquid oxygen
LRO	Lunar Reconnaissance Orbiter
LSC	Legal Subcommittee
LSP	Launch Services Program
LSST	Large Synoptic Survey Telescope
LST	Land Surface Temperature
LTS	Long-Term Sustainability
Lunar CATALYST	Lunar Cargo Transportation and Landing by Soft Touchdown

M

MAGIC CARPET	Maritime Augmented Guidance with Integrated Controls for Carrier Approach and Recovery Precision Enabling Technologies
MaGIXS	Marshall Grazing Incidence X-ray Spectrograph
MAIAC	Multi-Angle Implementation of Atmospheric Correction
MARS	Mid-Atlantic Regional Spaceport
MARSIS	Mars Advanced Radar for Subsurface and Ionosphere Sounding
MARSOC	Marine Special Operations Command
MAV	Mars Ascent Vehicle
MAVEN	Mars Atmosphere and Volatile EvolutioN
MCS-2	Mission Control System–2
MCSB-2	Mission Control System Backup–2
MDA	Missile Defense Agency
MDXR	Missile Defense Transfer Radiometer
MEDA	Mars Environmental Dynamics Analyzer
MEDLI	Mars Entry, Descent, and Landing Instrumentation
MEP	Manufacturing Extension Partnership
MER	Mars Exploration Rover
MESSENGER	MErcury Surface, Space ENvironment, GEochemistry, and Ranging
METOP-A/GRAS	Meteorological Operational satellite programme–A/Global navigation satellite system Receiver for Atmospheric Sounding
MEU	Marine Expeditionary Units
MIL-STD	Military Standard
MinXSS	Miniature X-ray Solar Spectrometer
MIT	Massachusetts Institute of Technology
MKID	Microwave Kinetic Inductance Detector
MMRTG	Multi-Mission Radioisotope Thermoelectric Generator
MMS	Magnetospheric Multiscale
MOA	Memorandum of Agreement

MoBE	Microbiology of the Built Environment
MOBY	Marine Optical Buoy
MODIS	Moderate Resolution Imaging Spectroradiometer
MOJA	Mojave National Preserve
MOPS	Minimum Operating Performance Standards
MOSA	Modular Open System Approach
MOU	Memorandum of Understanding
MOXIE	Mars Oxygen In Situ Resource Utilization Experiment
MPCV	Multi-Purpose Crew Vehicle
MPS	Mathematics and Physical Sciences
MRLC	Multi-Resolution Land Characteristics Consortium
MRO	Mars Reconnaissance Orbiter
MRX	Magnetic Reconnection Experiment
MSAD	Mission Systems Architecture Demonstrator
MSAVI2	Modified Soil Adjusted Vegetation Index II
MSFC	Marshall Space Flight Center
MSIs	Minority Serving Institutions
MSIP	Mid-Scale Innovations Program
MSV	Modular Space Vehicle
MTBS	Monitoring Trends in Burn Severity
MUOS	Mobile User Objective System
MWTA	Megawatt Tactical Aircraft

N

NACA	National Advisory Committee for Aeronautics
NAICS	North American Industry Classification System
NAIP	National Agricultural Imagery Program
NANOGrav	North American Nanohertz Observatory for Gravitational Waves
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NASCENT	National Airspace System Constraint Evaluation and Notification Tool
NASM	National Air and Space Museum
NASS	National Agricultural Statistics Service
NASTAR	National Aerospace Training and Research
NAVAIR	Naval Air Systems Command
NCEP	National Centers for Environmental Prediction
NCO	National Coordination Office
NDVI	Normalized Difference Vegetation Index
NE	Office of Nuclear Energy
NEA	Near-Earth Asteroid
NED	National Elevation Dataset
NEN	Near Earth Network
NEO	Near Earth Object
NERSC	National Energy Research Supercomputing Center
NERVA	Nuclear Engine for Rocket Vehicle Applications
NextGen	Next Generation; Next Generation Air Transportation System
NextSTEP	Next Space Technology for Exploration Partnerships
NFS	National Forest System
NGEE	Next Generation Ecosystem Experiment
NIAC	NASA Innovative Advanced Concepts
NICER	Neutron star Interior Composition Explorer
NICT	National Institute of Information and Communications Technology
NIFC-CA	Naval Integrated Fire Control–Counter Air
NIR	near-infrared

NIST	National Institute of Standards and Technology
NLCD	National Land Cover Database
NMNH	National Museum of Natural History
NNSA	National Nuclear Security Administration
NOAA	National Oceanic and Atmospheric Administration
NOAO	National Optical Astronomy Observatory
NOC	National Operations Center
NPP	National Polar-orbiting Partnership
NPS	National Park Service
NRA	NASA Research Announcement
NRAO	National Radio Astronomy Observatory
NRC	National Research Council
NRCS	Natural Resources Conservation Service
NROL	National Reconnaissance Office Launch
NSA	National Security Agency
NSF	National Science Foundation
NSO	National Solar Observatory
NSPO	National Space Organization
NSRL	NASA Space Radiation Laboratory
NSS	National Security Space
NSTC	National Science and Technology Council
NSWS	National Space Weather Strategy
NTF	National Transonic Facility
NTP	Nuclear Thermal Propulsion
NuDets	nuclear detonations
NuSTAR	Nuclear Spectroscopic Telescope Array
NWP	numerical weather prediction

O

OA	Orbital ATK; operational assessment
OBOGS	On-Board Oxygen Generation System
OCO	Orbiting Carbon Observatory
OCSD	Optical Communications and Sensor Demonstration
ODNI	Office of the Director of National Intelligence
OECD	Organization for Economic Cooperation and Development
OES	Bureau of Oceans and International Environmental and Scientific Affairs
OFII	Office of Finance and Insurance Industries
OGA	Office of Global Analysis
OGE	out-of-ground effect
OGS	Optical Ground Station
OLI	Operational Land Imager
OLYMPEX	Olympic Mountain Experiment
OMAC	Orbital Maneuvering Attitude Control
OMPS	Ozone Mapping Profiler Suite
ORACLES	ObseRvations of Aerosols above CLouds and their intEractionS
Orbital	Orbital Sciences Corporation/Orbital ATK
ORS	Operationally Responsive Space
OSBP	Office of Small Business Programs
OSD	Office of the Secretary of Defense
OSIRIS-REx	Origins, Spectral Interpretation, Resource Identification, Security–Regolith Explorer
OSTP	Office of Science and Technology Policy
OTA	other transaction authority
OTM	Office of Transportation and Machinery
OVERFLOW	OVERset grid FLOW solver

P

PACE	Plankton, Aerosols, Clouds, and ocean Ecosystem
PACOM	Pacific Command
PAR	Presidential Aircraft Recapitalization
PBN	Performance Based Navigation
PBS	Plum Brook Station
PCM HX	Phase Change Material Heat Exchanger
PDA	progressive damage analysis
PDL	Ponce de Leon
PDR	Preliminary Design Review
PeV	petaelectronvolt
PHY	Division of Physics
PLR	Division of Polar Programs
PMBSS	Primary Mirror Backplane Support Structure
PNT	Positioning, Navigation, and Timing
POES	Polar-orbiting Operational Environmental Satellites
POSEIDON	Ocean Topography Experiment
PP	Precision Point
PPPL	Princeton Plasma Physics Laboratory
PRS	Public Regulated Service
PSD	Planetary Science Division; production, supply, and distribution
PTMS	power and TMS
Pu	plutonium

Q

QCL	quantum-cascade laser

R

RCF	Range Communication Facility
RCS	Reaction Control System
RED	Regional Economic Development
RERP	Reliability Enhancement and Re-engining Program
RF-CLASS	Remote-Sensing-Based Flood Crop Loss Assessment Service System
RFMG	Radio Frequency Mass Gauge
RFP	Request for Proposal
RGFO	Royal Gorge Field Office
RHIC	Relativistic Heavy Ion Collider
RIME	Radar for Icy Moon Exploration
RISR	Resolute Bay Incoherent Scatter Radar
RLV	Reusable Launch Vehicle
RNP	Required Navigation Performance
RO	radio occultation
ROD	Record of Decision
ROK	Republic of Korea
ROSES	Research Opportunities in Space and Earth Sciences
Rp	refined propellant
RPA	Remotely Piloted Aircraft
RPS	radioisotope power system
RPT	Rocket Propulsion Test
RRSW	Rapid Response Space Works
RSAC	Remote Sensing Applications Center
RSCC	Remote Sensing Coordinating Committee

RSIWG	Remote Sensing Interagency Working Group
RTCA	Radio Technical Commission for Aeronautics

S

SAA	Sense and Avoid
SAB	Scientific Advisory Board
SABRS	Space and Atmospheric Burst Reporting System
SAC-C	Satélite de Aplicaciones Científicas
Saffire-1	Spacecraft Fire Experiment–1
SAL	Semi-Active Laser
SAM	Sample Analysis at Mars
SAMS	Sensitivity Analysis for Multidisciplinary Systems
SAO	Smithsonian Astrophysical Observatory
SAT	Special Action Team; Office of Space and Advanced Technology
SATCOM	Satellite Communications
SBAG	Small Bodies Assessment Group
SBAS	Satellite Based Augmentation System
SBIR	Small Business Innovative Research
SBIRS	Space Based Infrared System
SBP	Space Biology Program
SBSS FO	Space Based Space Surveillance Follow-On
SC	Office of Science
S-CAESAR	Small-Component and Engine Structural Assessment Research
SCaN	Space Communications and Navigation
SDD	System Development and Demonstration
SDO	Solar Dynamics Observatory
SEA	Social and Economic Analysis
SEP	solar electric propulsion
SEXTANT	Station Explorer for X-ray Timing and Navigation Technology
SGM	small guided munition
SHARAD	Shallow Subsurface Radar
SHIIVER	Structural Heat Intercept Insulation Vibration Evaluation Rig
SHINE	Solar, Heliosphere, and INterplanetary Environment
SIA	Satellite Imagery Archives
SIRCUS	Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources
SJRRP	San Joaquin River Restoration Program
SLAC	Stanford Linear Accelerator Center
SLC	Space Launch Complex
SLS	Space Launch System
SM	Service Module
SMA	Service Module Adapter
SMAP	Soil Moisture Active Passive
SMC	Space and Missile Systems Center
SMD	Science Mission Directorate
SMDC	Space and Missile Defense Command
SN	Space Network
SNaP	SMDC Nanosatellite Program
SNDD	Space-Based Nuclear Detonation Detection
SNL	Sandia National Laboratories
SNP	Saguaro National Park
SNSPD	superconducting nanowire single-photon detector
SO_2	sulfur dioxide
SOA	service-oriented architecture
SOC	Space Optical Clock

SOCOM	Special Operations Command
SOFIA	Stratospheric Observatory for Infrared Astronomy
SOHO	Solar and Heliospheric Observatory
SP	Service Pack
SpaceX	Space Exploration Technologies Corporation
SPB	Super Pressure Balloon
SPEI	Standardized Precipitation Evapotranspiration Index
SPMAGTF-SC	Special Purpose Marine Air Ground Task Force–Southern Command
SPO	System Program Office
SPP	Solar Probe Plus
SPT	South Pole Telescope
SPTpol	SPT polarization-sensitive
SPUD	Small Polarimeter Upgrade for Degree Angular Scale Interferometer
SQUID	Superconducting Quantum Interference Device
SRR	Sample Return Robot
SRTM	Shuttle Radar Topography Mission
SSA	Space Situational Awareness
SSC	Stennis Space Center
SSDP	Space Security and Defense Program
SST	Space Surveillance Telescope
SSTP	Small Spacecraft Technology Program
STA	structural test article
Stare WAI	Staring Wide Area Imager
STARS	Standard Terminal Automation Replacement System
STE	structural test equipment
STELR	Supersonic Engine for Long Range
STEM	science, technology, engineering, and mathematics
STEREO	Solar and Terrestrial Relations Observatory
STMD	Space Technology Mission Directorate
STMSat-1	St. Thomas More Cathedral School Satellite–1
STOVL	Short Take-Off and Vertical Landing
STP	Space Test Program
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
SWEAP	Solar Wind Electrons Alphas and Protons
SWIM	System Wide Information Management
SWIR	shortwave infrared
SWORM	Space Weather Operations, Research, and Mitigation
SWR	Space Weather Research
SZ	Sunyaev-Zel'dovich

T

TALISMAN	Tendon-Actuated Lightweight In-Space MANipulator
TAMR	Terminal Automation Modernization and Replacement
TBFM	Time Based Flow Management
TBW	Truss Braced Wing
TCC	Tree Canopy Cover
TCCON	Total Column Carbon Observing Network
TCL	Technology Capability Level
TDRS	Tracking and Data Relay Satellite
TDRSS	Tracking and Data Relay Satellite System

TECRO	Taipei Economic and Cultural Representative Office in the United States
TES	transition-edge sensor; Terrestrial Ecosystem Science
TESS	Transiting Exoplanet Survey Satellite
TeV	teraelectronvolt
TFDM	Terminal Flight Data Manager
TFMS	Traffic Flow Management System
THEMIS	Time History of Events and Macroscale Interactions during Substorms
TIGER	Topologically Integrated Geographic Encoding and Referencing
TM	Thematic Mapper
TMAS	Thermal Mapping Airborne Simulator
TMRR	Technology Maturation and Risk Reduction
TMS	thermal management system
TOPEX	Topography Experiment
TRACON	Terminal Radar Approach Control
TRL	Technology Readiness Level
TSA	Transportation Security Administration
TSAS	Terminal Sequencing and Spacing
TSC	Technical Service Center
TSIS	Total and Spectral Solar Irradiance Sensor
TT&C	telemetry, tracking, and communication

U

UAF	University of Alaska Fairbanks
UAS	unmanned aircraft system
UAV	Unmanned Aerial Vehicle
UCAR	University Corporation for Atmospheric Research
UDP	Unit Deployment Program
UGCS	Universal Ground Control Station
UHF	Ultra-High Frequency
ULA	United Launch Alliance
ULI	University Leadership Initiative
UNCOPUOS	United Nations Committee on the Peaceful Uses of Outer Space
UNISPACE+50	50th anniversary of the first United Nations conference on the Exploration and Peaceful Uses of Outer Space
UNOOSA	United Nations Office of Outer Space Affairs
URGB	Upper Rio Grande Basin
USAF	United States Air Force
USAID	U.S. Agency for International Development
USDA	U.S. Department of Agriculture
USFS	U.S. Forest Service
USGS	United States Geological Survey
USMC	United States Marine Corps
USNDS	U.S. NuDet Detection System
USSTRATCOM	U.S. Strategic Command
UTM	UAS Traffic Management

V

VASIMR	Variable Specific Impulse Magnetoplasma Rocket
VCLS	Venture Class Launch Service
Veggie	Vegetable Production System
VIIRS	Visible Infrared Imaging Radiometer Suite
VSMI	Vehicle Systems Model Integration
VSPT	Variable-Speed Power Turbine
VTOL	Vertical Take-Off and Landing

W

WASDE	World Agricultural Supply and Demand Estimates
WaterSMART	Sustain and Manage America's Resources for Tomorrow
WCDMA	Wideband Code Division Multiple Access
WFIRST	Wide Field Infrared Survey Telescope
WGS	Wideband Global SATCOM
WIN	Written Impact Narrative
WMAP	Wilkinson Microwave Anisotropy Probe
WMN	Western Range Modernization of Network
WSF	Weather Satellite Follow-on
WSTF	White Sands Test Facility
WUI	wildland urban interface

Z

ZTF	Zwicky Transient Facility

NP-2017-05-2391-HQ